System Frequency Scans for Underground Transmission Options using HVDC Light

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Technical Report

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System Frequency Scans for Underground Transmission Options using HVDC Light	Dept. **Consulting**	Date 10/1/04	Pages 246

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Executive Summary:

Northeast Utilities (NU) is presently pursuing transmission expansion in their system focused on establishing additional transmission capacity from the Northern parts of the system to Southwestern Connecticut. The present Phase II ac option for this transmission expansion is a combination of overhead and underground ac transmission. It consists of an overhead 345 kV line from Beseck to Devon, followed by 345 kV ac cables from Devon to Singer and then Singer to Norwalk. New 345 kV substations are also included.

There are 13 specific requirements set out with respect to the performance criteria of any transmission expansion proposed for Phase II. NU wishes to identify if any technically viable option exists for this Phase II project that utilizes a fully underground transmission solution that also satisfies all of the thirteen performance criteria. To this end, ABB's consulting group has been engaged to look at underground HVDC technologies as an option.

One of the key issues among the 13 performance criteria is to improve the point of the first system resonance to 3rd harmonic or higher. This is a problem with the all-ac Phase II option, even with the partial overhead transmission line from Devon to Beseck. This report specifically addresses this concern.

Through detailed network frequency scans, it has been shown in this study that:

1. First, the low-order harmonic resonance does exist (under the low-generation case) for the all-ac Phase II option. The resonance is between the 2nd and 3rd harmonic, and it is predominantly present on the 345-kV corridor from Beseck to Norwalk to Plumtree. ***It is thus concluded that the low-order harmonic resonance is mainly caused by the capacitive charging of the Phase I and Phase II ac cables.***
2. It is found that the light load case shows a slightly lower resonance frequency for the base system condition. This effect is more pronounced for the worst single contingency (outage of the Long Mountain – Plumtree 345 kV line). Removal of one of the two Norwalk-Plumtree HPFF cables during light load conditions helps to increase the frequency of the first resonance.
3. For an all-dc option using HVDC Light®, the low-order harmonic resonance on the system is eliminated, mainly because the Phase II ac cables are removed. The inherent low-impedance characteristic of the voltage source converters is also beneficial. The first resonant frequency is now above the 3rd harmonic. ***This satisfies the requirement of moving the network point of resonance above 3rd harmonic***.
4. For an alternative dc option, namely just replacing the overhead line between Devon and Beseck with dc, the inherent characteristic of the VSC helps to damp slightly and to shift up the frequency of resonance. The frequency of resonance is shifted to slightly above 3rd harmonic in most cases and is a little more damped. Further damping may also be possible through active filtering at 3rd harmonic with the VSCs.
5. As stated in item 1 above, the dominating factor that results in the low-order harmonic resonance is the capacitive charging of the ac cables. Thus, by removing the ac cables with the all-dc solution a major part of the problem is eliminated. Other solutions that include ac cables are likely not as effective as an all-dc (with HVDC Light®) solution in moving the resonance above 3rd harmonic.

Thus, based on the analysis presented here, from the perspective of low-order harmonic resonance the all-dc option using voltage source converter technology seems quite favorable.

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1 Introduction

Northeast Utilities is presently pursuing transmission expansion in their system focused on establishing additional transmission capacity from the Northern parts of the system to Southwestern Connecticut. The present Phase II ac option for this transmission expansion is a combination of overhead and underground ac transmission. It consists of an overhead 345 kV line from Beseck to Devon, followed by 345 kV ac cables from Devon to Singer and then Singer to Norwalk. New 345 kV substations are also included. This is depicted in Figure 1.

On August 6th, ABB was approached by Northeast Utilities (NU), United Illuminating Company and the New England ISO to develop a fully underground solution, based on High-Voltage dc (HVDC) technology, that would have the same or better performance than the all-ac option described above and shown in Figure 1.

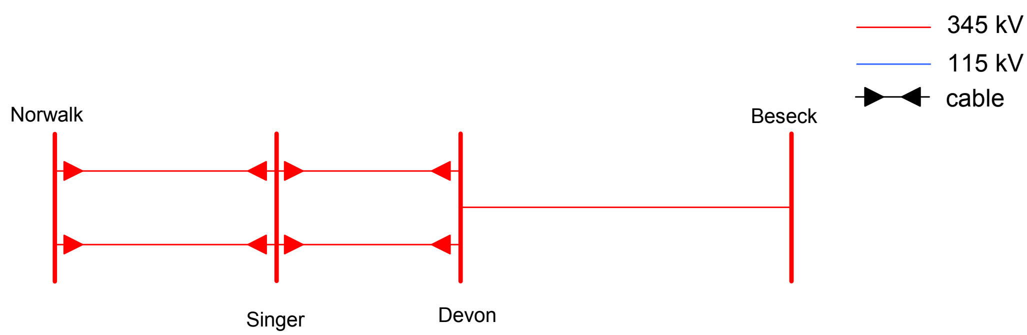


Figure 1: All-ac Phase II Option

There are thirteen specific requirements set out with respect to the performance criteria of any transmission expansion proposed for Phase II. These requirements are set forth in Appendix A. This report addresses item 4.

The item for review in this report is the requirement to improve the point of the first system resonance to 3rd harmonic or higher. This report comprises three parts. Section 2 discusses the potential concerns with low-order harmonic resonance. Section 3 discusses the modeling, study methodology and assumptions for this work. Section 4 presents the conclusions.

2 Concerns With Low-Order Harmonic Resonance

ABB understands that Northeast Utilities wishes to keep the first resonance in the system above the 3rd harmonic. The concern is that if there is a low-order harmonic resonance in the ac network, then events such as transformer bank energization or single-line to ground faults and clearing could in extreme cases yield high and sustained overvoltages. Such overvoltages may be damaging to equipment.

The phenomenon can be explained as follows. Upon transformer energization or at fault clearing, the inrush (magnetization) current of a transformer has dc, 2nd, 3rd, 4th and higher order harmonic content, with decreasing magnitude for increasing harmonic order. If there is a low-order harmonic resonance in the system, it is possible that, for extreme cases involving energization of large transmission transformers (i.e. 100's of MVA), these harmonic currents may meet a high network impedance, resulting in overvoltages. Of course, this would require that the low-order harmonic resonance is of sufficient magnitude (i.e. many tens to hundreds of ohms), and that there is a significant source of harmonic current. As a first approach, one would attempt to design the system to avoid such low-order harmonic resonances.

It is ABB's understanding that three design options for the Phase II system in southwestern Connecticut have been previously considered:

1. The 345 kV ac cable option from Devon to Norwalk
2. A solution with conventional (line commutated) HVDC converters
3. An HVDC solution with voltage source converter technology

ABB has been asked to further investigate option 3 above. In the first case above (345 kV ac cable from Devon to Norwalk), the low-order resonance arises from the large amount of capacitive charging of the ac cables. Because the capacitance is inherent to the ac cables, this low-order resonance is difficult to mitigate.

In the second case above (conventional, line-commutated HVDC), the ac cables are replaced with dc cables. This eliminates the effect of cable capacitance on the ac network. However, conventional HVDC converters have two aspects that can give rise to a low order harmonic resonance:

1. Conventional HVDC converters use large amounts of shunt capacitive compensation in the form of ac filters and shunt capacitors at their terminals.
2. The dc smoothing reactor in a conventional HVDC converter gives a high internal impedance at harmonic frequencies when viewed from the ac bus, and thus the converter acts as a harmonic current source.

The large amount of shunt compensation used in conventional HVDC converters can give rise to a low-order resonance for weak ac system conditions. If the resonance is above the 2nd harmonic, it can be mitigated by the inclusion of a low-order filter. This technique has been used successfully for many conventional HVDC projects around the world. If, however, the ac network resonance is at the 2^{nd} harmonic, then this implies extremely weak ac network conditions. Conventional (line commutated) HVDC converters are not normally designed to operate into such a weak ac network because of other constraints.

For extremely weak conditions, the third option above (HVDC with voltage source converter technology) has been successfully employed. Voltage source converters are used in ABB's HVDC Light® technology, and can operate into an ac network with no short circuit availability (i.e. a network comprising only loads, with no generators). HVDC Light® uses IGBT switch-mode converters, with high-frequency pulse width modulation (PWM) switching. The characteristics of the HVDC Light® converters are fundamentally different from conventional HVDC in the following respects:

1. The high-frequency PWM switching means that the characteristic harmonics are at high frequencies, and can therefore be filtered using much smaller (lower MVAR) filters as compared to conventional HVDC.
2. Since it is a voltage source converter, the converter has low internal impedance at harmonic frequencies as viewed from the ac bus.

The combination of the two aspects above gives a dramatic improvement in the conditions at low-order harmonic frequencies as compared to solutions with conventional HVDC and solutions with ac cables. The improvement is in three respects: (1) HVDC Light® eliminates the capacitance of the ac cables, which is the main concern; (2) The ac filters for HVDC Light® are much smaller than for conventional HVDC, helping to raise the lowest resonant frequency; and (3) the filters are shunted by the phase reactor and the low internal impedance of the converter.

Thus, of the various options considered, HVDC Light® technology offers the best opportunity to improve the conditions at low-order harmonic frequencies as compared to the other two options above.

3 Modeling, Study Methodology and Assumptions

3.1 Model Development and Assumptions

The system model was based on the power flow data supplied by Northeast Utilities. The power flow cases used were *phase2-alt2-091503-2.SAV and test.SAV* (Phase II light load case derived by NU from *light-ph2-alt2-101603.SAV*). Starting with these models, the following assumptions were made:

1) The network characteristic impedances to be calculated (in the vicinity of Norwalk, Devon, Singer etc.) are primarily influenced by the power system in the state of Connecticut. Thus, the rest of the Eastern Interconnection was equivalenced.
2) The frequency scans were performed using lumped pi-section models for all transmission lines and cables, based on the impedance data provided in the power flow case. This is a reasonable (and conservative) assumption for network frequency scans up to perhaps the 6 or 7th harmonic. For higher frequencies, skin effects, network impedance unbalance, and other high-frequency phenomena lead to significantly different behavior, and as such it becomes exceedingly difficult to model such non-linear behavior (i.e. frequency dependence of network losses etc.). Thus, at the higher system frequencies, frequency scan analysis is somewhat dubious. Since low-order harmonics are of main interest in this study, such considerations have minimal impact on the results presented.
3) All generators were modeled as a voltage source behind their respective subtransient reactance (X''d) in series with armature resistance (ra). Note: To perform a frequency scan, a voltage source is a short circuit to ground by definition. Thus, the generator models effectively become a series ra + jX''d from the terminals to ground.
4) A positive sequence network model was built based on the power flow database.
5) All loads were represented as described in Appendix B. The load level was modeled as represented in the power flow database.

Thus, an ac network model of the system was developed ready for performing frequency scans. The data used was that presented in the power flow database (and for machine impedances those presented in the dynamics database *ph1-lightt_AES_2B2-part.dyr*). Figure 2 is a simplified diagram of the model developed, showing the model boundaries. The source impedances, as calculated using the power flow data, are listed in Appendix C.

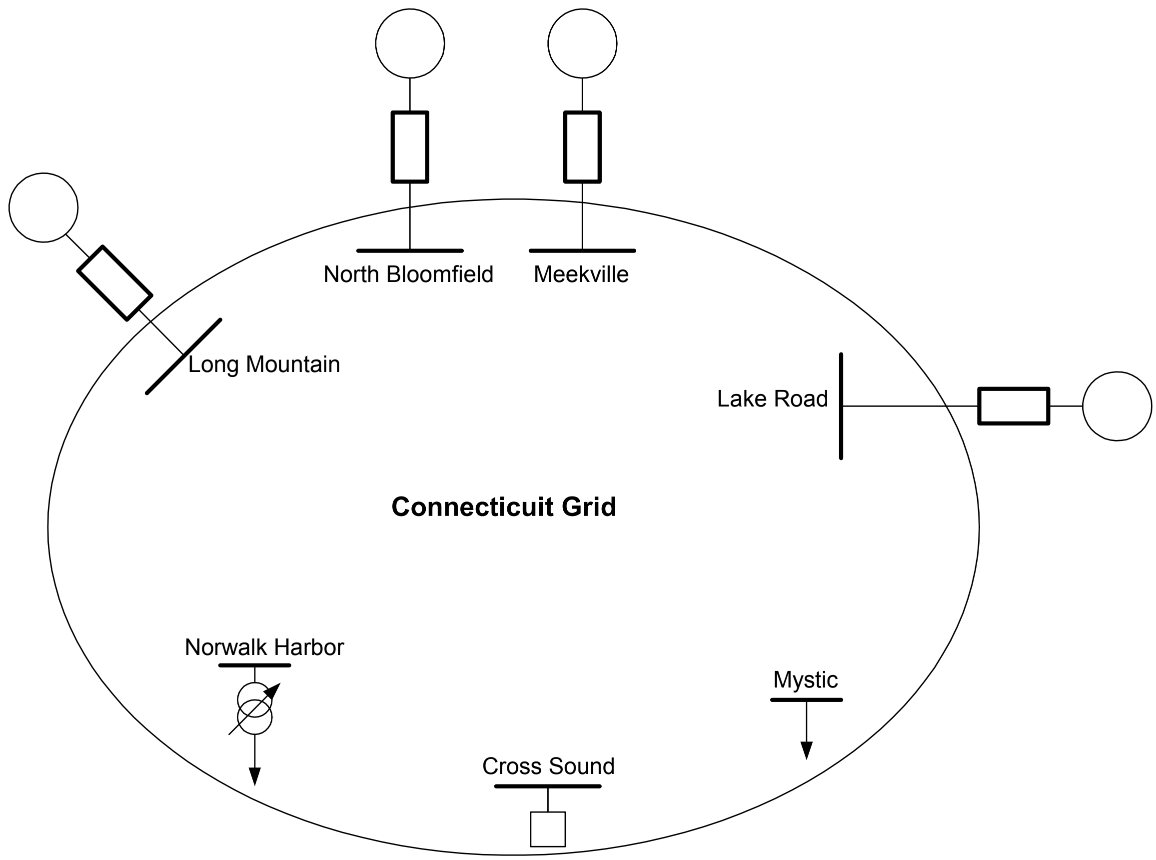


Figure 2: Network Model

3.2 Cases Studied and Study Methodology

As described above, an ac network model representing the entire Connecticut power grid was developed. Then the following items were checked:

1) All shunt capacitor banks in the Connecticut system were placed in-service.
2) All local generation in the Southwestern region were turned off-line.

The list of generators in the model that were out of service, and the list of all shunt capacitors in the power flow case are provided in Appendix C. These additional changes lead to pessimistic conditions, namely low generation combined with high shunt compensation in the Southwestern region of Connecticut. Based on separate work performed by consultants for Northeast Utilities [1], it was found that under these conditions the network experienced the most onerous low-order harmonic resonance (at roughly 150 Hz with a peak of approximately 130 ohms). A similar frequency and magnitude resonance with the existing Phase II all-ac option was calculated in the model developed for this study. In addition, the model was also modified for Phase I ac conditions and compared to work performed by consultants for Northeast Utilities [2]. These comparisons confirm the validity of the model for further analysis.

The study approach included consideration of the following system aspects:

1) System load levels: 100%, 40%
2) Shunt capacitor banks for 100% and 40% loadings per customer-supplied loadflow cases
3) Base conditions and conditions with line outage contingencies

The results of the analysis are presented in Section 3.5. Section 3.4 describes the converter model for frequency scan purposes. In the analysis presented here, conditions with both Phase I ac cables (Norwalk-Plumtree) in service are depicted unless otherwise indicated. The Bridgeport generation at Singer is off-line.

3.3 Converter Rating

Two different terminal power ratings have been considered, 370 MW and 530 MW delivered to the receiving ac network. Note that for this feasibility study, the per unit base MVA used to define the impedance of the transformer and the phase reactor for connecting the 370 MW and 530 MW converters to the ac system are 384 MVA and 504 MVA, respectively.

Note that converter ratings can be increased somewhat with additional cooling. The final converter size for the SWCT project will be optimized in the design stage. Given the available converter sizes, it is possible to find a combination that will provide 1200 MW capacity or more to meet the project needs. Another point to note is that the study has shown that the results are not significantly affected by the exact power ratings of the converters. The per unit impedance of the converter transformer and phase reactors are based on 384 MVA and 504 MVA. Frequency scans for both converter sizes established that the results are not significantly different.

3.4 Converter Model

Figure 3 shows a high level diagram of the converter main circuit for ABB's HVDC Light® technology. The converter is a voltage source converter (VSC) that uses insulated gate bipolar transistors (IGBT). A pulse width modulation (PWM) control strategy effects forced commutation.

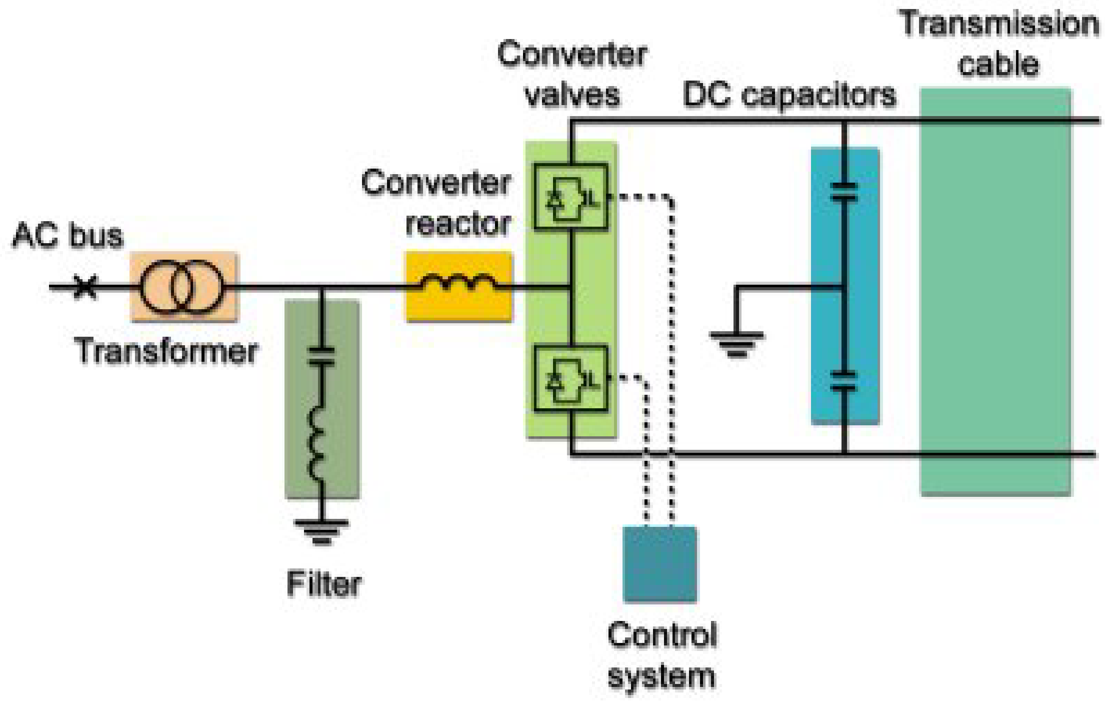


Figure 3: HVDC Light Converter Station

With PWM switching at high frequencies (in the kilohertz range), it is possible to create any phase angle or amplitude (up to the converter rating) by changing the PWM pattern. Further, changes in the phase angle or amplitude can be made very quickly if needed. Thus, VSC converters offer the possibility to fully, and independently, control both active and reactive power.

From the perspective of the system, the VSC is effectively an ideal voltage source much like a generator, controlling active and reactive power almost instantaneously. However, it does not significantly contribute to the short circuit level on the ac system, since the converter current is controlled and limited during disturbances.

As shown in Figure 4 (for a two-level converter), the PWM-bridge switches at high frequency between two fixed dc voltages. For a three-level design (not shown), additional IGBT switches are included to allow the output to be connected at any given time instant to either of the two dc voltages or to the neutral. By controlling the time duration at each of the dc voltages for each PWM cycle, a fundamental ac voltage of desired magnitude and phase is created. The desired fundamental frequency voltage is then low-pass filtered through a series phase reactor.

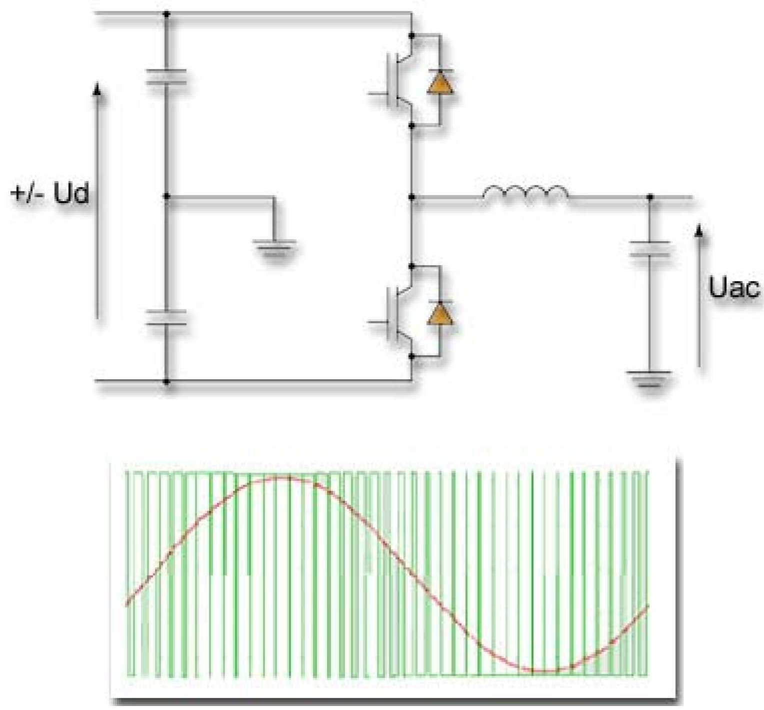


Figure 4: Pulse Width Modulation (PWM) Control of a Voltage Source Converter

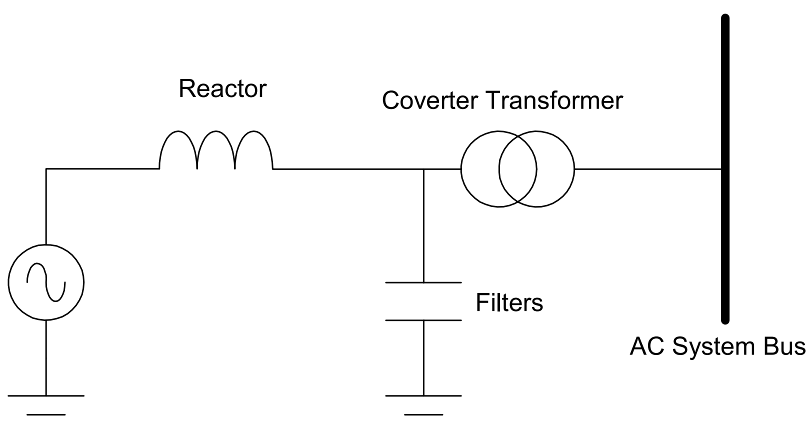


Figure 5: Voltage Source Converter Model, Valid at Fundamental and Low-Order Harmonic Frequencies (not valid for short circuit calculations)

Figure 5 shows a representation of the VSC valid for representation at fundamental and low-order harmonic frequencies. It is noted that, for short circuit conditions, the converter current is normally limited to the level of the pre-fault converter loading.

Reference [3] describes the natural behavior of the voltage source converter at harmonic frequencies up to 6^{th} harmonic, using a detailed model of the converter circuit, and representing static conditions without controls. It is shown in [3] that the natural impedance of the converter is low at harmonic frequencies.

The results in Reference [3] show that the natural behavior of a VSC HVDC system can be regarded as the "dual" of conventional (line-commutated) HVDC. In a line-commutated converter (conventional HVDC), the large smoothing reactor size ensures low dc current ripple. Consequently, the converter harmonic impedance is high when viewed from the ac side, and the converter acts as a harmonic current source.

Conversely, in a voltage source converter (HVDC Light®), a large dc capacitor is used in order to ensure low dc voltage ripple. The converter impedance at harmonic frequencies is therefore low when viewed from the ac side. The voltage source converter thus acts as a harmonic voltage source

The results shown in [3] have been verified by additional simulations using a detailed model of the HVDC Light® converter in PSCAD. The detailed model represents all relevant converter controls in detail. Two main PWM control modes are used in HVDC Light®: one for steady-state conditions, with a separate control mode used for dynamic (transient) conditions. Both control modes were investigated in PSCAD. For steady-state conditions, the PSCAD simulations show a low converter harmonic impedance, as expected. Moreover, the impedance is capacitive at 2^{nd} and 3^{rd} harmonics, and well damped (low phase angle). The capacitive characteristic of the steady-state control mode is beneficial in that it cancels part of the inductive impedance of the phase reactor and transformer, resulting in a low overall impedance at 2^{nd} and 3^{rd} harmonics as viewed from the main utility bus.

For the dynamic control mode, which acts during post-fault recovery or recovery from other disturbances, it is expected that digital filtering will be included in the controls to obtain the desired characteristics at the low harmonic orders. With digital filters, the PSCAD results show low impedance (a few ohms), with low phase angle. Conditions without digital filters were also investigated to bracket the worst-case conditions. Without digital filters, the PSCAD results show impedance values of around 150 ohms, again with a well-damped phase angle. This means that the converter exhibits a well-damped (resistive) behavior with or without digital filters included in the controls. The impedance magnitude of the converter is also highly selectable by the designer, even for the dynamic control mode. In this respect, optimization of the converter behavior will be performed during the design stage.

Resistive values of zero and 150 ohms were considered in the study to bracket the possible conditions for the dynamic control mode. Additionally, the capacitive impedance of the steady-state control mode was investigated in the study.

When performing the frequency scans, the VSC was modeled by the representation shown in Figure 6. The impedance Zconv was chosen as described above to represent the steady-state and dynamic characteristics of the controls.

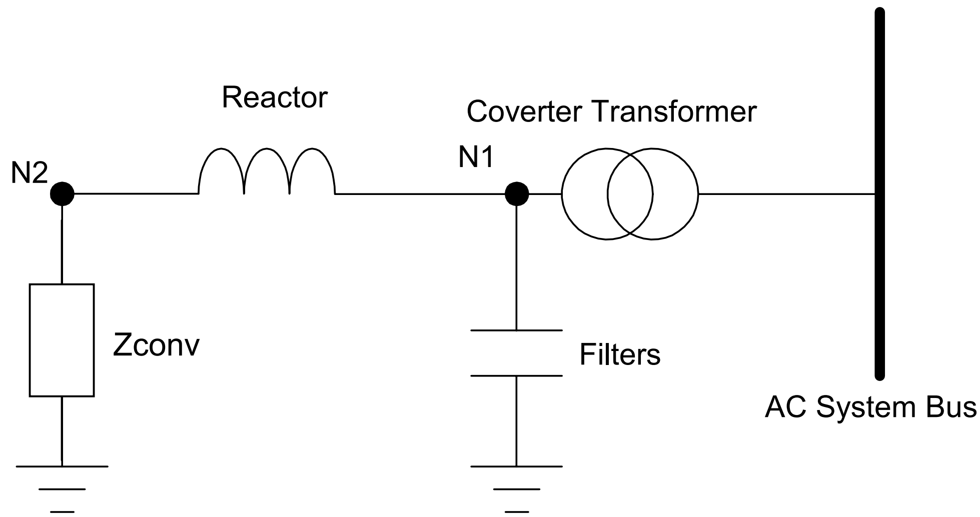


Figure 6: Model of voltage source converter for frequency scans

For the 530 MW rated converter, the transformer impedance is 12%, total amount of filters is 15% and the size of the phase reactor is 16.8%. All of these values are on a 504 MVA base as described in Section 3.3. The transformer X/R is assumed to be 40, while the reactor Q factor is assumed to be 200. Converter losses were not modeled. This is conservative, as losses contribute damping at harmonic frequencies.

Note that, as described in Section 3.1, the developed model depicts positive sequence conditions. This technique is consistent with the method used in previous studies performed for NU [1, 2] and with industry practice. It is noted that a wye-delta transformer is used for the converter, and, depending on the final design, the transformer may give either a low (leakage) impedance for zero sequence or behave as an open circuit. An option to use an ungrounded wye or delta on the utility side is under consideration, in order to eliminate converter contribution to single line-to-ground ac faults. This would result in an open circuit for zero sequence. In this condition, the HVDC light system itself would be benign (neither helping nor hurting the impedance conditions), but it is emphasized that the predominant beneficial effect of removing the Phase II ac cables, and their charging capacitance, exists for both positive and zero sequence. Therefore, the first resonance for zero sequence with the all-dc option is improved (raised in frequency) as compared to the Phase II ac option, regardless of the transformer connection used in the final design.

For information, reference [4] describes the sequence components of inrush harmonic currents from offset saturated transformers. It is noted that only banks of three single-phase transformers give predominantly zero sequence third harmonic current. For three-phase transformers (core-form and shell-form), the third harmonic current includes positive, negative, and zero sequence components, and the zero sequence component is much lower as compared to banks of three single-phase transformers.

3.5 Study Cases

The following cases were studied:

1) **Phase II ac solution:** The base case Phase II ac solution as represented in the original power flow case. This is shown in Figure 1. Frequency scans were also performed for this option for a select number of N-1 contingencies (listed in Table 1).
2) **DC options 1 and 2:** The Phase II ac solution was removed from the case. This was done by removing the 345 kV substations at Devon and Singer, as well as the cables from Norwalk to Singer to Devon and the overhead transmission line from Devon to Beseck. In addition, all substation transformers (345/115) and shunt reactors at Singer and Devon 345 kV were removed. Instead, three HVDC Light® converters were modeled at Norwalk and Beseck 345 kV, as well as two converters at Pequonnock and East Devon 115 kV. This represents both HVDC options 1 and 2 in Figure 7. Frequency scans were performed both for the base case and select N-1 ac and N-2 dc outages (Table 1).
3) **DC option 3:** The 345 kV overhead line from Devon to Beseck was replaced by three parallel HVDC Light® converters (Figure 7). For this option, only the base case was investigated (Table 1).

Table 1: Contingencies Studied

Contingency No.	Description
1**	Devon to Beseck 345 kV out
2	Long Mountain to Plumtree 345 kV out
3	Norwalk 345/115 kV transformer out (one bank only)
4**	Singer 345/115 kV transformer out
5**	Devon 345/115 kV transformer out
6	Plumtree to Norwalk 345 kV (Phase I) cable out (both circuits)
7**	One circuit of Norwalk to Singer 345 kV cable out
8**	One circuit of Singer to Devon 345 kV cable out
9*	Two converters off-line at Norwalk and Beseck
10*	Two converters off-line at Singer/Pequonnock
11*	Two converters off-line at Devon

* **Note:** Contingencies 9, 10 and 11 are actually N-2 outages, and are only applicable to the HVDC option.
** These contingencies are only applicable to the all-ac option.

For the base and worst contingency cases found in the above analysis, the following additional sensitivity analyses were performed:

1) **Effect of system load level:** 100% versus 40% (light load) conditions
2) **Effect of converter impedance representation:** converter impedances for steady-state and dynamic control modes as identified in PSCAD simulations

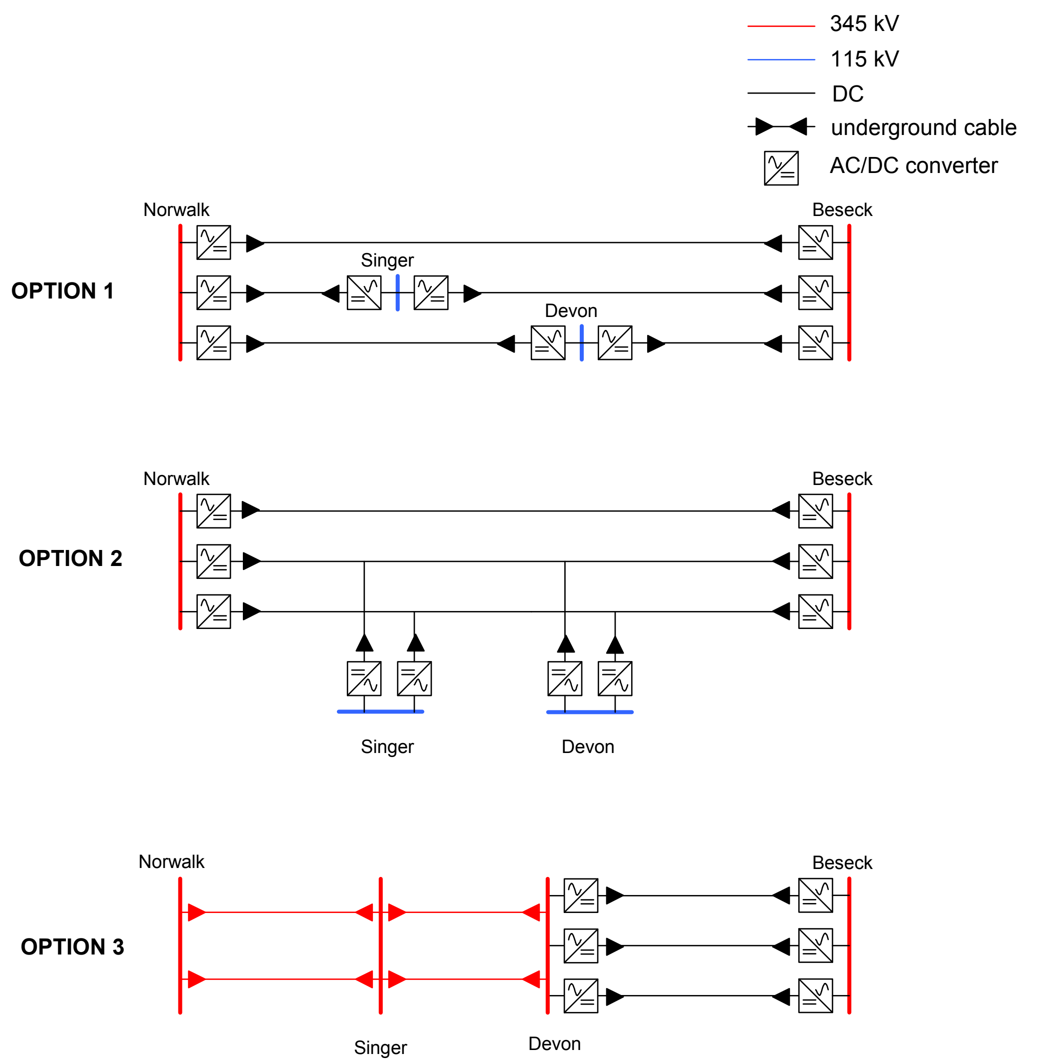


Figure 7: HVDC Options Studied

For the dc options, most of the analysis was performed assuming 530 MW rated converters for all the dc lines. Some sensitivity analysis was performed assuming all 370 MW converters (similar in size to Cross Sound). This helps to illustrate that the general conclusions are applicable to both converter sizes. The actual choice of converter size will be based on power flow and other technical studies and considerations. The intent here was simply to illustrate that low-order harmonics are not a concern with either HVDC Light® converter size.

The plots of all the results are presented in Appendix D as follows. Note that, unless otherwise indicated, the cases were run with two Norwalk-Plumtree HPFF cables in service.

Figures D-1 to D-9 show comparisons between the Phase II all-ac (Figure 1) option and the dc options 1 & 2 (Figure 7) for full load conditions with all capacitor banks in service.
Figures D-10 to D-102 show the same comparisons for the various contingencies listed in Table 1 for full load conditions with all capacitor banks in service.
Figures D-103 to D-111 show the comparison between the all-ac option and dc Option 3 (Figure 7) for full load conditions with all capacitor banks in service.
Figures D-112 to D-120 show comparisons between the Phase II all-ac (Figure 1) option and the dc options 1 & 2 (Figure 7), but with the smaller converter size (i.e. 370 MW rated converters) for full load conditions with all capacitor banks in service.
Figures D-121 to D-156 show comparisons between the Phase II all-ac (Figure 1) option and the dc options 1 & 2 (Figure 7) for 40% load conditions, and with capacitor banks in service consistent with 40% load conditions per the customer-supplied light load powerflow case. Base conditions and Plumtree-Long Mountain contingency considered, as well as variation of converter impedance from zero to 150 ohms.
Figures D-157 to D-192 show comparisons between the Phase II all-ac (Figure 1) option and the dc options 1 & 2 (Figure 7) for 40% load conditions, and with capacitor banks in service consistent with 40% load conditions per the customer-supplied light load powerflow case. Base conditions and Plumtree-Long Mountain contingency considered, as well as variation of converter impedance from zero to 150 ohms. One Plumtree-Norwalk HPFF cable in service.
Figures D-193 to D-210 show comparisons between the Phase II all-ac (Figure 1) option and the dc options 1 & 2 (Figure 7) for 40% load conditions, and with capacitor banks in service consistent with 40% load conditions per the customer-supplied light load powerflow case. Base conditions and Plumtree-Long Mountain contingency considered. Converter impedance for steady-state control mode investigated.

For all cases, system impedance frequency scans were performed at the buses listed in Table 2.

Table 2: Busses Scanned for System Impedance Frequency Scans

Bus Number	Bus Name and kVDescription
73293	Norwalk 345 kV
73295	Beseck 345 kV
73297	Devon 345 kV
73129	Devon 115 kV
73313	Singer 345 kV
73700	Pequonnock 115 kV
73115	Plumtree 345 kV
73106	Southington 345 kV
73686	Woodmont 115 kV

3.6 Study Results

Because of the extremely large number of plots shown in Appendix D, some key results are brought forward for comparisons of various conditions. These results are given in Figures 8-15 as follows:

Figure 8: Norwalk 345 kV bus: base conditions, zero converter impedance.
Figure 9: Plumtree 345 kV bus: base conditions, zero converter impedance.
Figure 10: Norwalk 345 kV bus: base conditions, 150 ohm converter impedance.
Figure 11: Plumtree 345 kV bus: base conditions, 150 ohm converter impedance.
Figure 12: Norwalk 345 kV bus: Long Mountain-Plumtree contingency, zero converter impedance.
Figure 13: Plumtree 345 kV bus Long Mountain-Plumtree contingency, zero converter impedance.
Figure 14: Norwalk 345 kV bus Long Mountain-Plumtree contingency, 150 ohm converter impedance.
Figure 15: Plumtree 345 kV bus: Long Mountain-Plumtree contingency, 150 ohm converter impedance.

The following additional figure is presented to summarize the effect of the converter representation:

Figure 16: Norwalk 345 kV bus: investigation of sensitivity to converter impedance for 40% system load conditions.

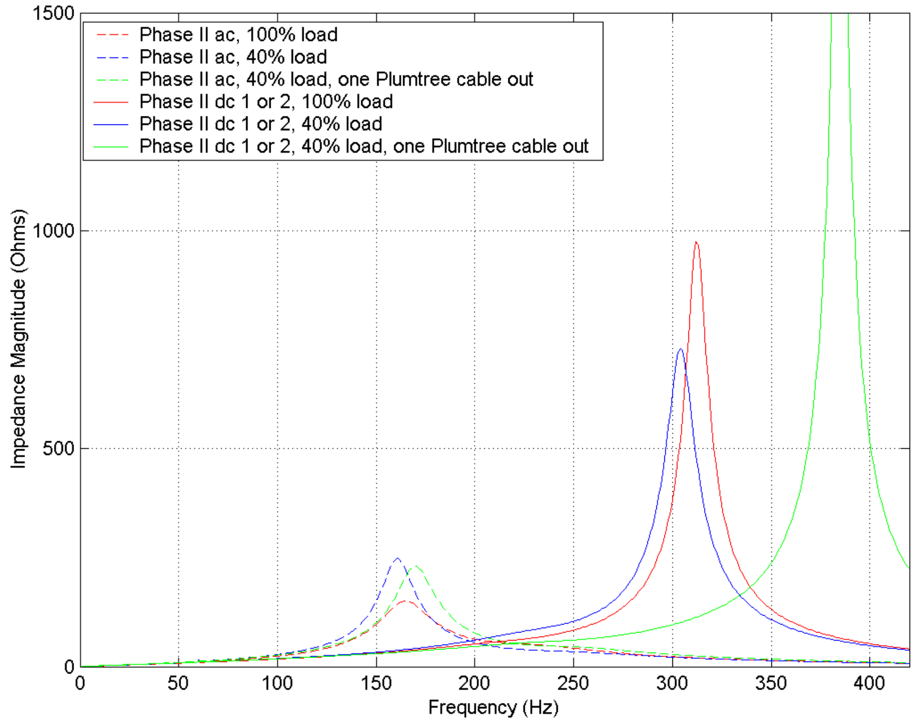


Figure 8. Norwalk 345 kV bus, Base Conditions, Zero Converter Impedance

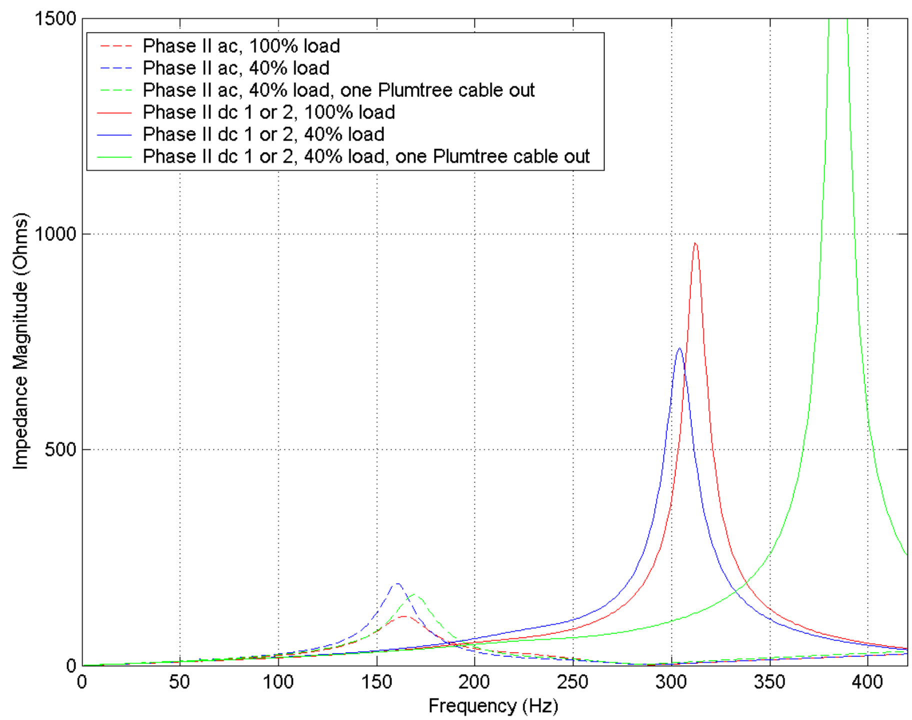


Figure 9. Plumtree 345 kV bus, Base Conditions, Zero Converter Impedance

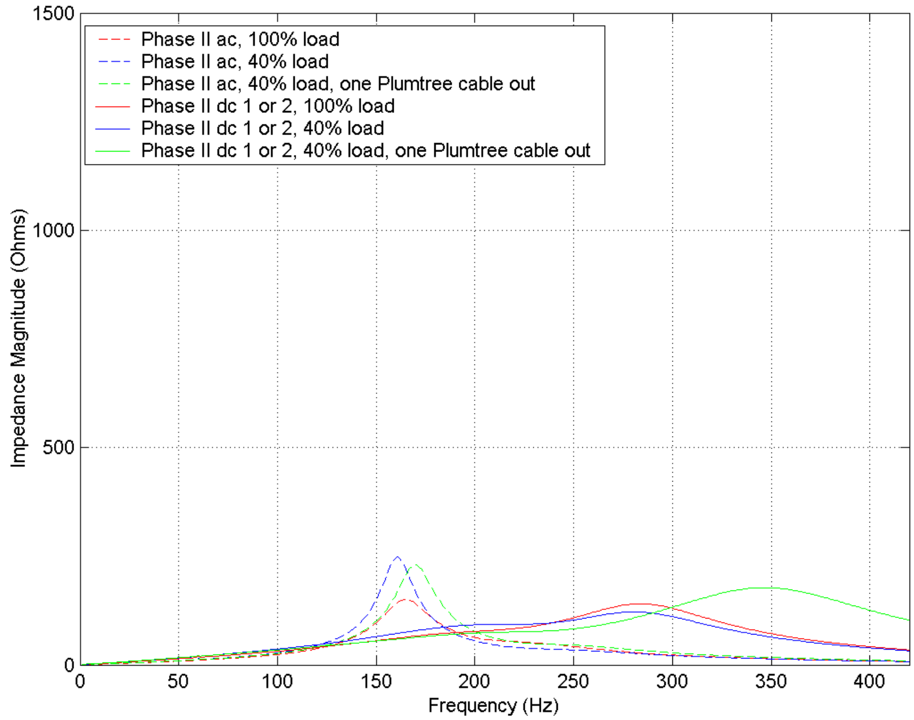


Figure 10. Norwalk 345 kV bus, Base Conditions, 150Ω Converter Impedance

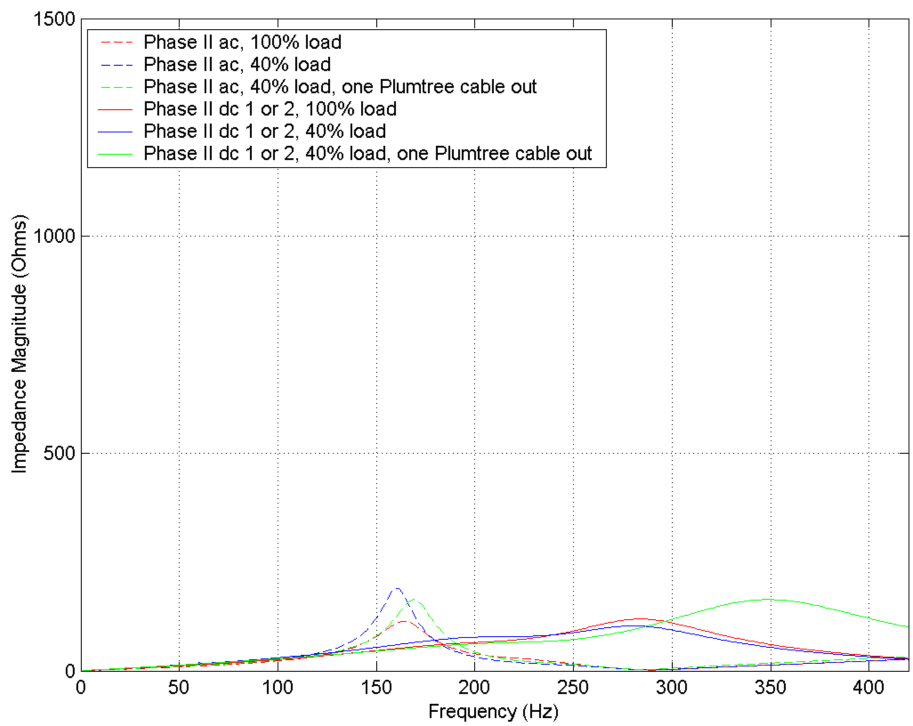


Figure 11. Plumtree 345 kV bus, Base Conditions, 150Ω Converter Impedance

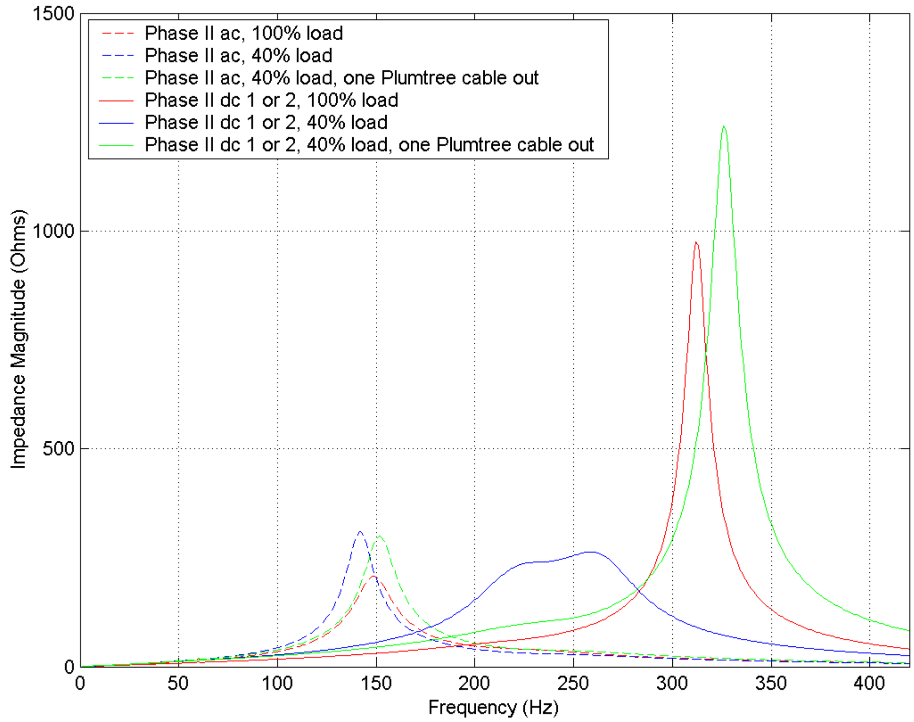


Figure 12. Norwalk 345 kV, Long Mtn – Plumtree Out, Zero Converter Impedance

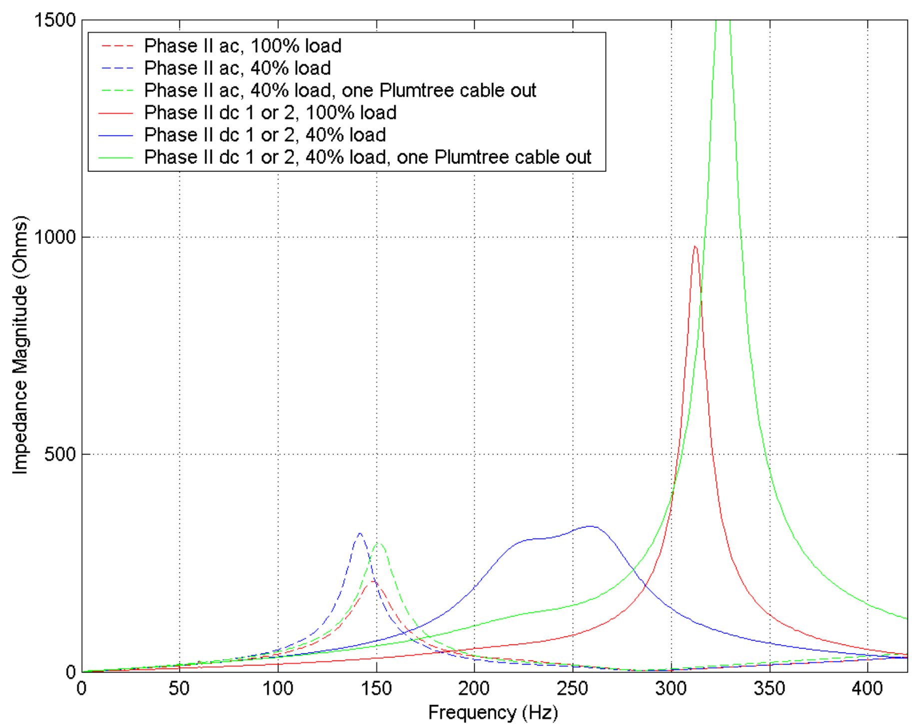


Figure 13. Plumtree 345 kV, Long Mtn – Plumtree Out, Zero Converter Impedance

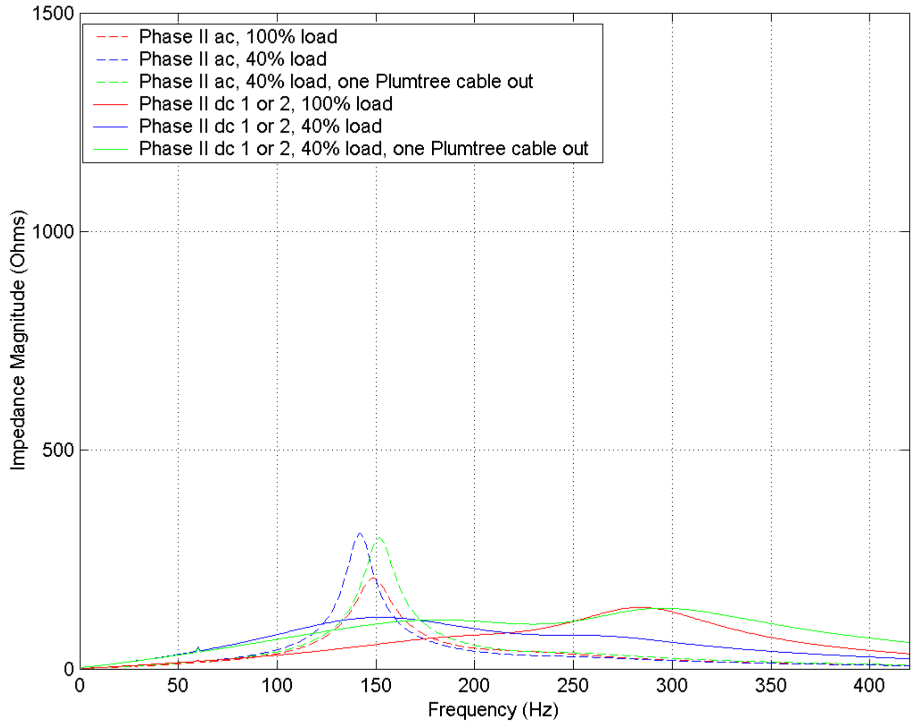


Figure 14. Norwalk 345 kV, Long Mtn – Plumtree Out, 150Ω Conv. Impedance

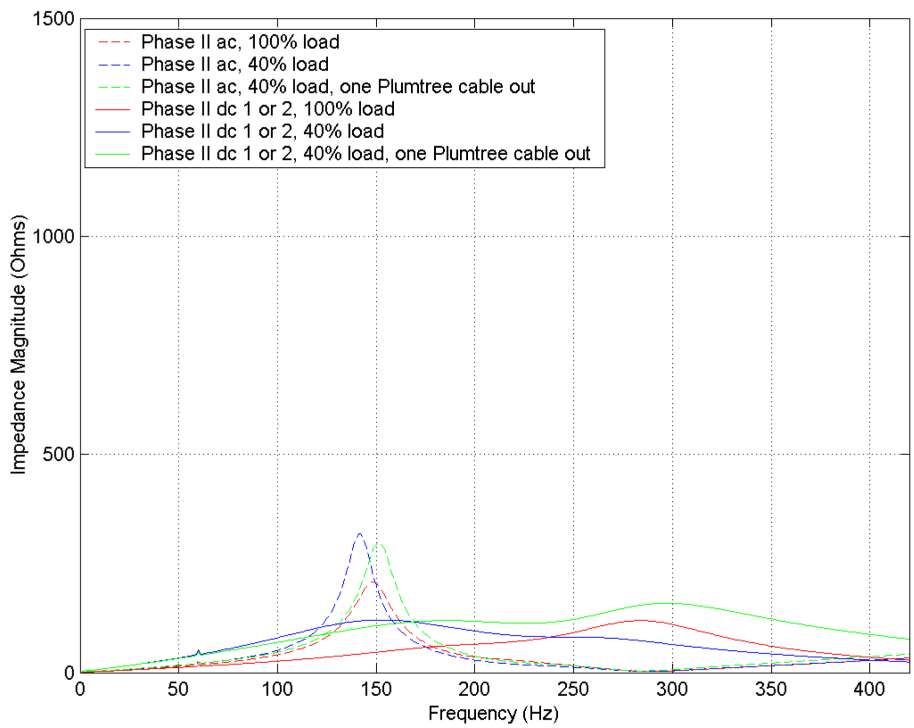


Figure 15. Plumtree 345 kV, Long Mtn – Plumtree Out, 150Ω Conv. Impedance

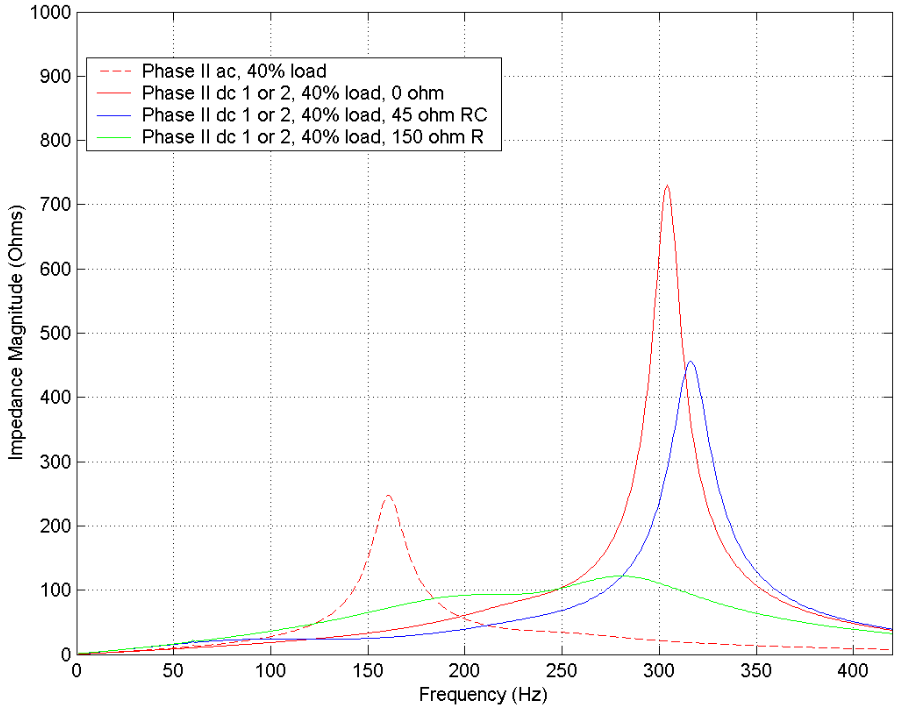


Figure 16. Norwalk 345 kV, Base Conditions, Sensitivity to Converter Impedance

Considering the results in Figures 10, 11, 14, 15, and 16, it should be noted that the cases with 150-ohm converter impedance are unrealistically pessimistic, and are only included to bracket worst-case conditions. For example, the converter impedance at 3rd harmonic is much lower than 150 ohms when digital filtering is included, and therefore the impedance at 3rd harmonic in Figures 10, 11, 14, 15, and 16 is unrealistically high. Modeling of the converter as 150 ohms for all low harmonic orders thus gives very conservative conditions. These results are shown only because detailed design of the control is project-specific and has not been finalized for the Southwest Connecticut system. The PSCAD simulations show that the harmonic impedances can be brought to very low values when digital filters are included in the controls.

Based on all results, the following observations are made:

1. First, based Figures D-1 to D-9, the following conclusions are made:
    a. A low-order harmonic resonance does exist for the all-ac Phase II option,
    b. It is between the 2nd and 3rd harmonic,
    c. It is predominantly present at the 345 kV level (it is quite damped at 115 kV), and
    d. On the 345 kV system it is observed on the Beseck – Norwalk – Plumtree corridor.

    Based on these observations, it is concluded that the main cause of the low-order harmonic resonance in the Phase II all-ac option is the capacitive charging of the Phase I and Phase II ac cables.

2. DC Options 1 & 2: For the all-dc option, the low-order harmonic resonance on the system is eliminated, mainly because of the removal of the Phase II ac cable. The inherent low-impedance characteristic of the voltage source converters is also found to be beneficial. The first resonant frequency is now above the 3rd harmonic, even considering worst-case conditions. ***This satisfies the requirement (see Appendix A) of moving the network point of resonance above 3rd harmonic***.
3. DC Option 3: For dc option 3, the inherent low-impedance characteristic of the VSC helps to damp slightly and to shift up the frequency of resonance. The frequency of resonance is now slightly above 3rd harmonic and a little more damped.
4. 370 MW Converters: For dc options 1 & 2, the sensitivity case of making all of the dc converters the lower rated units (370 MW converters, rather than 530 MW) makes little difference in the results.
5. Effect of System Load: Comparing results with 100% system load versus 40% system load, it is observed that the light load case shows a slightly lower resonance frequency for the base system condition. This effect is more pronounced for the worst single contingency (outage of the Long Mountain – Plumtree 345 kV line). The 100% system load case shows higher resonance frequency because the load adds a resistive component in parallel with the shunt capacitors. Note that the model used for the load includes resistive, inductive, and motor load components in typical proportions for distribution feeders as shown in Appendix B.
6. Effect of Contingencies: Outage of the Long Mountain – Plumtree 345 kV circuit results in worst-case contingency conditions, particularly when two Norwalk-Plumtree HPFF cables are in service. It is not clear that this contingency was studied in prior work [1], [2], and thus the conditions may be unrealistic. Removal of one Norwalk-Plumtree HPFF cable improves the system conditions significantly.
7. Effect of Converter Representation: The effects of the control mode and corresponding representation of the converter have been studied, and found not to alter the overall conclusion that the all-dc Phase II system shows acceptable low-order harmonic performance.
8. Effect of Norwalk-Plumtree HPFF cables: The frequency scan results show that removal of one Norwalk-Plumtree HPFF cable during light system load conditions offers the opportunity to increase the first resonance frequency (see Figures 8-15). With the all-dc option, two Norwalk-Plumtree HPFF cables may be used during 100% system load conditions.

A 5th harmonic resonance is observed in the all-dc Phase II option (1 or 2) for some cases. This is not a concern, based on the following discussion.

First, it should be noted that a 5th harmonic resonance on the 345-kV system will not typically have any adverse impact to the system. A 345-kV system normally does not have any significant 5th harmonic current sources, and therefore no problems are expected. It is actually common for systems with larger capacitor banks installed to have resonance in this range and operate without any problems.

Another option with HVDC Light® technology is the ability to effect active harmonic filtering. That is, the VSC controls may be tuned to actively damp out certain harmonic frequencies. This capability is in addition to the inherent (low harmonic impedance) characteristics of the VSC described in Section 3.4. This active filtering is achieved by measuring the voltage on the ac side of the converter and purposely creating a harmonic voltage using the VSC that is equal in magnitude but 180 degrees opposite in phase to any measured harmonic voltage on the system at the frequency of concern. In that way the VSC actively cancels out harmonic components on the ac side of the converter. Typically, this is done on the low side of the converter transformer (node N1 in Figure 6). Such active filtering is presently exercised for the 5th and 7th harmonic at Cross Sound. Thus, such active filtering may be used to damp out 5th harmonic resonance for the dc options 1 & 2, and 3rd harmonic for dc option 3.

Another way of addressing the 5th harmonic resonance observed for dc options 1 & 2, if desired, is to provide a passive filter tuned to 5th harmonic on the ac side of the ac/dc converter. Simply for illustrative purposes, a passive filter was designed and applied at the Norwalk converter stations in the dc options 1 & 2. One of the existing HVDC filters was doubly tuned, mainly to 21st harmonic but with some filtering at 5th. In this way, the total amount of filter shunt capacitive MVAr was not changed. The results of applying the filter are shown in Figure 17. Note that the filter shown in Figure 17 is not an optimally designed filter, but rather intended simply to illustrate the point that the 5th harmonic resonance can be addressed, if desired, by passive filtering as well as active filtering.

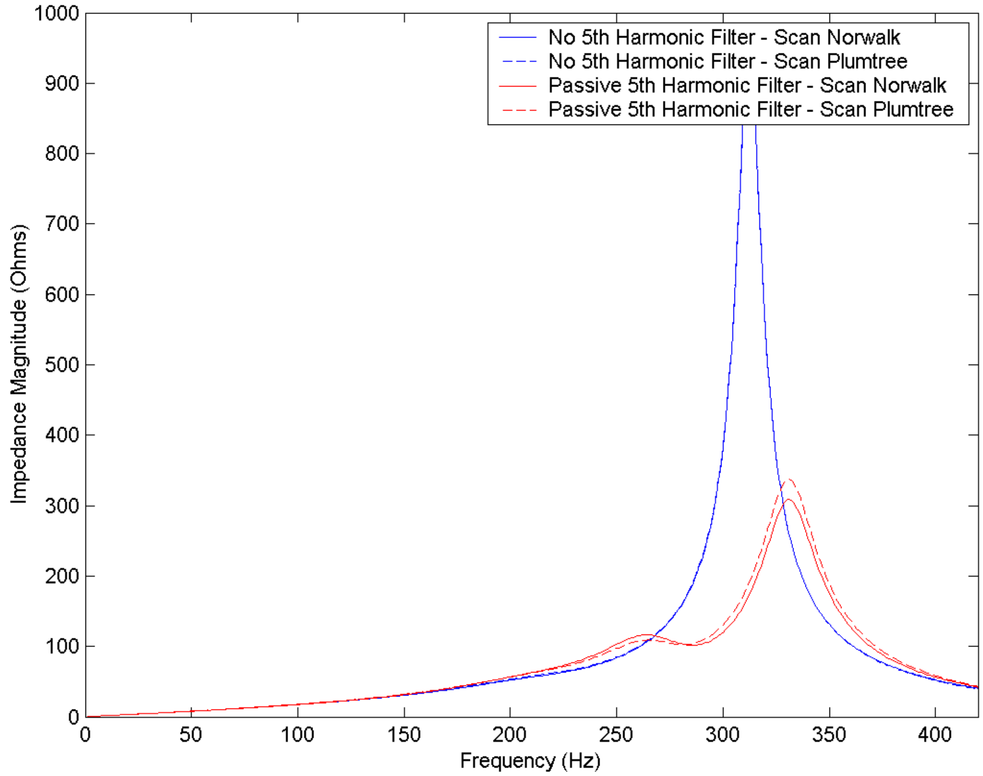


Figure 17: Passive Filtering to Eliminate 5th Harmonic Resonance. All Scans Shown are Applicable to DC Options 1 & 2

4 Conclusions

Northeast Utilities (NU) is presently pursuing transmission expansion in their system focused on establishing additional transmission capacity from the Northern parts of the system to Southwestern Connecticut. The present Phase II ac option for this transmission expansion is a combination of overhead and underground ac transmission. It consists of an overhead 345 kV line from Beseck to Devon, followed by 345 kV ac cables from Devon to Singer and then Singer to Norwalk. New 345 kV substations are also included.

NU has established 13 specific requirements for performance of any transmission expansion proposed for Phase II. NU wishes to identify if any technically viable option exists for this Phase II project that utilizes a fully underground transmission solution that also satisfies all of the thirteen performance criteria. To this end ABB's consulting group has been engaged to look at underground HVDC technologies as an option.

One of the key issues among the 13 performance criteria is to improve the point of the first system resonance to 3rd harmonic or higher. This is a problem with the all-ac Phase II option, even with the partial overhead transmission line from Devon to Beseck. This report specifically addresses this concern.

Through detailed network frequency scans, it has been shown in this study that:

1. First, a low-order harmonic resonance does exist (under the low-generation case) for the all-ac Phase II option. The resonance is between the 2nd and 3rd harmonic, and it is predominantly present at the 345 kV level. The resonance occurs in the 345-kV corridor from Beseck to Norwalk to Plumtree. ***Therefore, it can be concluded that the low-order harmonic resonance is mainly caused by the capacitive charging of the Phase I and Phase II ac cables.***
2. Comparing results with 100% system load versus 40% system load, it is observed that the light load case shows a slightly lower resonance frequency for the base system condition. This effect is more pronounced for the worst single contingency (outage of the Long Mountain – Plumtree 345 kV line). The study results also showed that the all-dc Option 1 and 2 solution still demonstrates acceptable frequency response at the lower load levels, while for the all-ac solution the problem of low order harmonic resonance still remains.
3. For an all-dc option using HVDC Light®, the low-order harmonic resonance on the system is eliminated, mainly because of the removal of the Phase II ac cable. The inherent low-impedance characteristic of the voltage source converters is also found to be beneficial. The first resonant frequency is now above the 3rd harmonic. ***This satisfies the requirement of moving the network point of resonance above 3rd harmonic***.
4. For an alternative dc option, namely just replacing the overhead line between Devon and Beseck with dc, the inherent characteristic of the VSC helps to damp slightly and to shift up the frequency of resonance. The frequency of resonance is shifted to slightly above 3rd harmonic in most case and is a little more damped. In

general, this case only marginally meets the criteria of pushing the harmonic resonance above 3rd harmonic. Further damping may be possible through active filtering at 3rd harmonic with the VSCs.

5. As stated in item 1 above, the dominating factor that results in the low-order harmonic resonance is the capacitive charging of the ac cables. Thus, by removing the ac cables with the all-dc solution a major part of the problem is eliminated. Other solutions that include ac cables are likely not as effective as an all-dc (with HVDC Light®) solution in moving the resonance above 3rd harmonic.
6. The effects of the HVDC control mode and corresponding representation of the converter have been studied, and found not to alter the overall conclusion that the all-dc Phase II system shows acceptable low-order harmonic performance.
7. The frequency scan results show that removal of one Norwalk-Plumtree HPFF cable during light system load conditions offers the opportunity to increase the first resonance frequency (see Figures 8-15). With the all-dc option, two Norwalk-Plumtree HPFF cables may be used during 100% system load conditions.

Thus, based on the analysis presented here, from the perspective of low-order harmonic resonance the all-dc option using voltage source converter technology seems quite favorable.

References

[1] S. Y. Lee, E. R. Pratico and R. A. Walling, "Connecticut Cable Resonance Study for XLPE Alternative in Middletown to Norwalk Project", July 2004, Summary Report issued by GE Energy.

[2] G. Drobnjak, M. A. Eitzmann, S. Y. Lee, E. R. Pratico and R. A. Walling, "Connecticut Cable Transient and Harmonic Design Study for Phase I", June 2003, Final Report issued by GE Energy.

[3] G. Asplund, ABB Memorandum dated 8/11/04. (A copy is being issued with this report)

[4] R. Walling, A. Khan, "Characteristics of Transformer Exciting Current During Geomagnetic Disturbances," IEEE Transactions on Power Delivery, Vol. 6, No. 4, October 1991.

APPENDIX A: System Criteria for Middletown to Norwalk Project

1. To be capable of moving approximately 1200 MW of power into Southwest Connecticut. Approximately 1200MW of power injection (800MW incremental after Phase II, and Phases I & II give 1400MW; comparison of transfer capacity for both AC and DC line outages.)

2. Resolve short circuit issues at Pequonnock 115kV and Devon 115kV and Devon 115kV target of 90% of 63kA or below.

3. Resolve generation interdependencies at Pequonnock, Devon, and Norwalk Harbor.

4. Improve the point of the first system resonance to 3rd harmonic or higher.

5. Provide a means of interconnecting new generation.

6. Have the ability to add new load serving stations as required.

7. Must be able to operate throughout a load cycle and throughout the year with varying dispatches and line outages.

8. The project cannot cause any new overloads on the system.

9. Respect technical and physical limitations.

10. The project needs to result in a dynamically stable system.

11. The project needs to provide adequate voltage on the system.

12. Respect existing contracts and system capabilities – cannot degrade capabilities such as the 352 MW (330MW net) capability of the Cross Sound Cable and 200MW across the 1385 submarine cable between Norwalk Harbor and Northport, LI.

13. Adverse Sub-synchronous Torsional Interaction (SSTI) effects should not be present – System must not act to destabilize torsional modes of nearby generators.

APPENDIX B: Load Models

The load model is import in calculating the network frequency response. The load model here is based on a synthetic approach that builds on the knowledge of the actual load power (real and reactive), typical feeder characteristics, a fixed basis for division between resistive and motor load, and a fixed basis for motor power-factor correction.

The synthetic feeder model used in this study has the following components:

Ratio of feeder loading to feeder transformer rating = 0.6 p.u.
Fraction of active power load that is resistive = 0.40 p.u.
Feeder reactance on own base = 0.15 p.u.
Feeder X/R ratio = 10:1
Ratio of motor load to rating = 0.9
Motor sub-transient reactance on own base = 0.2 p.u.
Motor loss on motor base = 0.10
Feeder capacitive compensation, p.u. of feeder rating = 0.4 p.u.

APPENDIX C: Shunts and Generator Status for Power Flow Case

The following tables show the shunt capacitors/reactors that are in-service in the case (Table C-1) and the generators that are disconnected in the case (Table C-2). The source (positive sequence) impedance at model boundaries, as calculated using the power flow data is presented in Table C-3.

Table C-1: In-Service Shunt Compensating Devices

Bus #	Bus Name	KV	Full Load Shunt B (pu on 100 MVA)	Light Load Shunt B (pu on 100 MVA)
73153	BRANFORD	115	0.378	0.000
73154	SGTN B	115	1.572	0.000
73162	WATERSDE	115	0.396	0.000
73168	GLNBROOK	115	1.908	0.000
73177	MYSTICCT	115	0.504	0.000
73190	ROCK RIV	115	0.252	0.000
73198	SOUTHGTN	115	1.512	0.000
73202	FROST BR	115	2.58	0.000
73210	MONTVLLE	115	1.048	0.524
73230	HADDAM	115	0.378	0.000
73242	MANCHSTR	115	3.144	0.524
73243	BERLIN	115	1.32	0.000
73244	N.BLMFLD	115	1.572	0.000
73260	FRKLN DR	115	0.393	0.000
73262	CANTON	115	0.524	0.000
73267	DARIEN	115	0.396	0.000
73396	CANTON	23	0.054	0.054
73398	N.CANAAN	13.2	0.048	0.048
73464	N.BLMFLD	23	0.108	0.108
73465	FARMNGTN	23	0.144	0.144
73466	NEWINGTN	23	0.054	0.054
73665	CROS SND	191.5	1.030	1.030
73668	E.SHORE	115	0.84	0.000
73671	NO.HAVEN	115	0.42	0.000
73672	SACKETT	115	0.42	0.000
73728	E.SHORE	13.8	0.2576	0.093
73730	QUINIPAC	13.8	0.5112	0.184
73731	NO.HAVEN	13.8	0.3083	0.111
73732	SACKETT	13.8	0.3857	0.139
73735	MIX AVE	13.8	0.5125	0.184
73736	MILLRIV1	13.8	0.314	0.113
73737	MILLRIV2	13.8	0.307	0.110
73738	BROADWAY	13.8	0.2923	0.105
73740	WATER ST	13.8	0.4217	0.152
73742	ELMWEST	13.8	0.4511	0.162

Bus #	Bus Name	KV	Full Load Shunt B (pu on 100 MVA)	Light Load Shunt B (pu on 100 MVA)
73744	ALLINGS	13.8	0.3563	0.128
73746	WOODMONT	13.8	0.4551	0.164
73748	MILVON	13.8	0.3737	0.134
73752	BARNUM	13.8	0.3417	0.123
73754	BAIRD	13.8	0.4872	0.175
73756	CONGRESS	13.8	0.4978	0.173
73760	PEQUONIC	13.8	0.2296	0.083
73763	ASHCREEK	13.8	0.5525	0.199
73764	TRAP FLS	13.8	0.5379	0.152
73765	DERBY PH	13.8	0.4872	0.175
73766	ANSONIA	13.8	0.287	0.103
73767	JUNE ST	13.8	0.3123	0.112
73770	HAWTHORN	13.8	0.339	0.122
73768	OLDTWN1	13.8	0.1061	0.038
73769	OLTWN2&3	13.8	0.3476	0.105
73755	CONGRES2	13.8	0.21	0.086
1003	STONYCAP	115	0.252	0.000
73135	NOROH	345	-2.25	-0.75
73132	PLUMREAC	345	-0.75	-0.75
73310	DEVSING1	345	-0.8	-1.30
73311	DEVSING2	345	-0.8	-1.30
73312	SINGDEV1	345	-0.8	-1.40
73313	SINGDEV2	345	-0.8	-1.40
73314	SINGNOR1	345	-1	-1.40
73315	SINGNOR2	345	-1	-1.40
73316	NORSING1	345	-1	-1.40
73317	NORSING2	345	-1	-1.40

Table C-2: Generators Out-of-Service

Bus #	Bus Name	kV	Generator ID
73163	COS COB	115	A
73163	COS COB	115	B
73163	COS COB	115	C
73187	STEVENSN	115	1
73277	DEVON10	115	9
73278	MONT DSL	115	A
73278	MONT DSL	115	B
73341	SHEPAUG	69	1
73381	BULLS BR	27.6	1
73537	RVRSD PF	23	1
73541	ROCK RIV	13.8	1
73543	FRKLN DR	13.2	A
73544	TUNNEL	23	A
73549	SMD1112J	13.8	1

Bus #	Bus Name	kV	Generator ID
73549	SMD1112J	13.8	2
73550	SMD1314J	13.8	3
73550	SMD1314J	13.8	4
73551	NORHAR#1	18	1
73552	NORHAR#2	20	2
73556	MIDDTN#3	22	3
73557	MIDDTN#4	22	4
73570	DEVGAS11	13.8	1
73571	DEVGAS12	13.8	1
73572	DEVGAS13	13.8	1
73573	DEVGAS14	13.8	1
73574	MILFD#1	13.8	1
73575	MILFD#2	13.8	1
73588	MERIDEN1	21	1
73589	MERIDEN2	21	1
73594	WALL LV1	13.8	1
73594	WALL LV1	13.8	2
73595	WALL LV2	13.8	1
73595	WALL LV2	13.8	2
73596	WALL LV3	13.8	1
73647	BPTHBR#2	20	2
73648	BPTHBR#3	22	3
73649	BPTHBR#4	13.8	4
73657	ENGLISH7	13.8	1
73658	ENGLISH8	13.8	1
73652	BE 11	16	1
73653	BE 12	16	1
73654	BE 10 ST	16	1
73590	MERIDEN3	21	1
73293	NORWALK	345	1
73297	DEVON	345	1
73301	SINGER	345	1
73168	GLNBROOK	115	S
73188	BCNFL PF	115	1
73188	BCNFL PF	115	2
73188	BCNFL PF	115	3
73203	CAMPV PH	115	1
73203	CAMPV PH	115	2
73276	LISBN PF	115	1
73280	RKRIV PF	115	2
73281	EXETR PF	115	1
73351	BATES DA	0.48	A
73352	SANDH DB	0.48	B
73353	SANDH DC	0.48	C
73459	WNDSRLK	27.6	1
73536	FORST PF	13.8	1

Bus #	Bus Name	kV	Generator ID
73542	FALLS V	6.9	1
73546	SMEAD PF	23	2
73546	SMEAD PF	23	1
73564	MIDD#10J	13.2	A
73616	SCRRA PF	69	1
73617	TUNNEL	69	2
73631	WLNGF PF	115	1
73765	DERBY PH	13.8	1

Table C-3: Boundary Source Impedances

Node	Impedance in pu on 100 MVA
Long Mountain 345 kV	0.00095 + j0.01661
North Bloomfield 115 kV	0.00945 + j0.06804
Meekville 345 kV	0.00189 + j0.02924
Lake Road 345 kV	0.00095 + j0.01347

APPENDIX D: Simulation Plots for Network Frequency Scans

Figures D-1 to D-9 show comparisons between the Phase II all-ac (Figure 1) option and the dc options 1 & 2 (Figure 7) for full load conditions with all capacitor banks in service.

Figures D-10 to D-102 show the same comparisons for the various contingencies listed in Table 1 for full load conditions with all capacitor banks in service.

Figures D-103 to D-111 show the comparison between the all-ac option and dc Option 3 (Figure 7) for full load conditions with all capacitor banks in service.

Figures D-112 to D-120 show comparisons between the Phase II all-ac (Figure 1) option and the dc options 1 & 2 (Figure 7), but with the smaller converter size (i.e. 370 MW rated converters) for full load conditions with all capacitor banks in service.

Figures D-121 to D-156 show comparisons between the Phase II all-ac (Figure 1) option and the dc options 1 & 2 (Figure 7) for 40% load conditions and with capacitor banks in service consistent with 40% load conditions. Base conditions and Plumtree-Long Mountain contingency considered, as well as variation of converter impedance from zero to 150 ohms.

Figures D-157 to D-192 show comparisons between the Phase II all-ac (Figure 1) option and the dc options 1 & 2 (Figure 7) for 40% load conditions and with capacitor banks in service consistent with 40% load conditions. Base conditions and Plumtree-Long Mountain contingency considered, as well as variation of converter impedance from zero to 150 ohms. *One Plumtree-Norwalk HPFF cable in service*.

Figures D-193 to D-210 show comparisons between the Phase II all-ac (Figure 1) option and the dc options 1 & 2 (Figure 7) for 40% load conditions and with capacitor banks in service consistent with 40% load conditions. Base conditions and Plumtree-Long Mountain contingency considered. Converter impedance for steady-state control mode investigated.

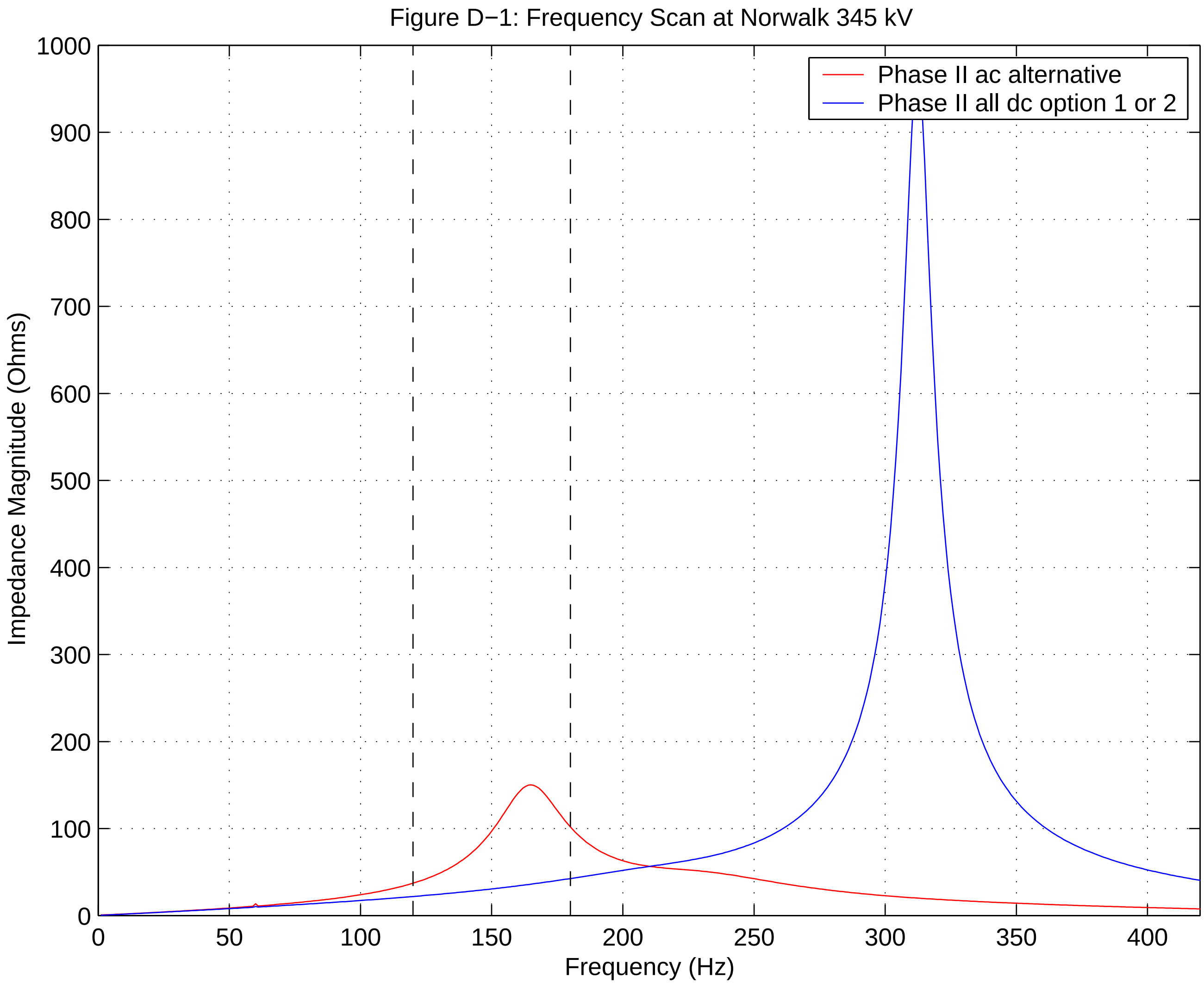
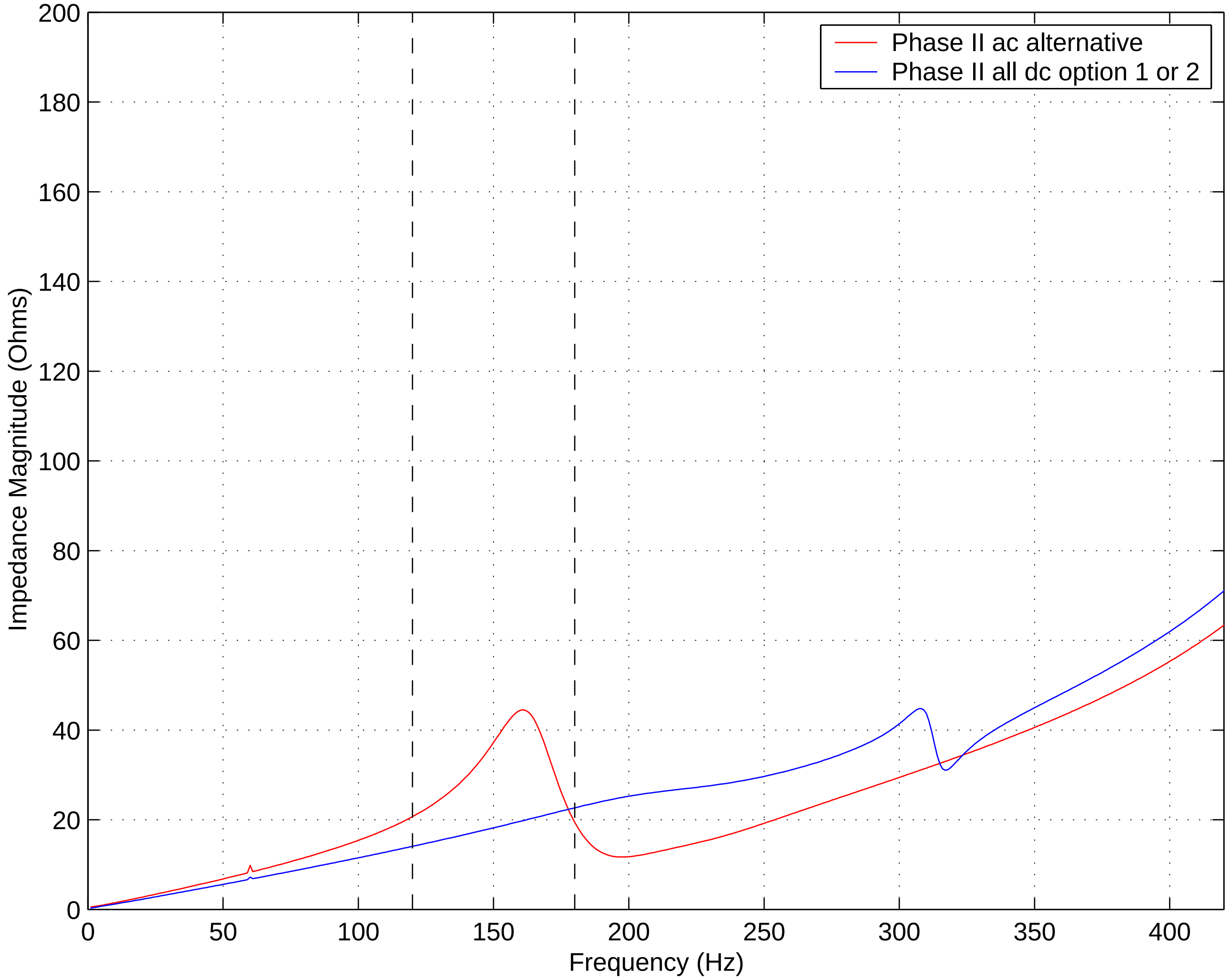


Figure D−1: Frequency Scan at Norwalk 345 kV
Phase II ac alternative
Phase II all dc option 1 or 2
Impedance Magnitude (Ohms)
Frequency (Hz)
0
100
200
300
400
500
600
700
800
900
1000
0
50
100
150
200
250
300
350
400

Figure D−2: Frequency Scan at Beseck 345 kV



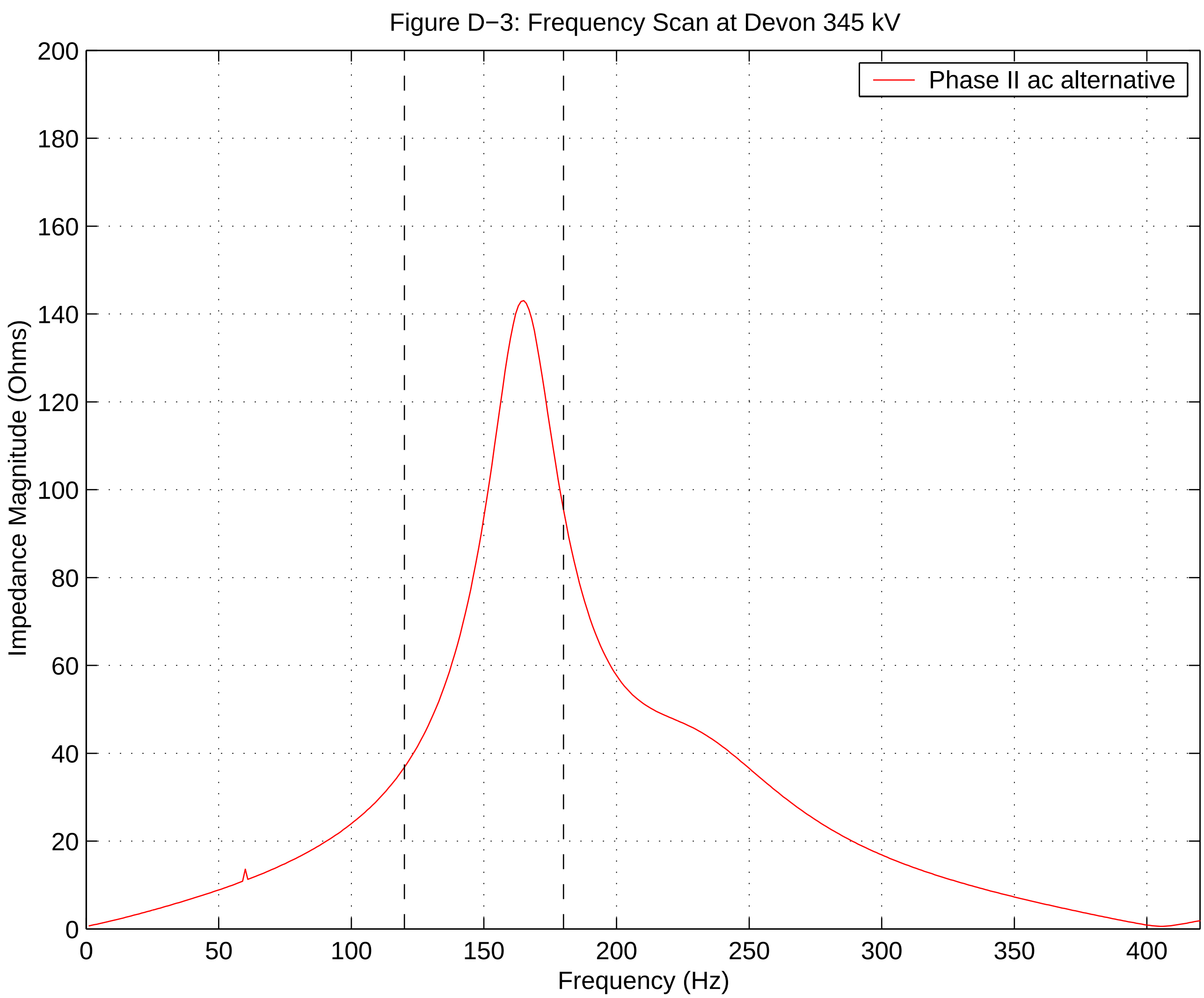
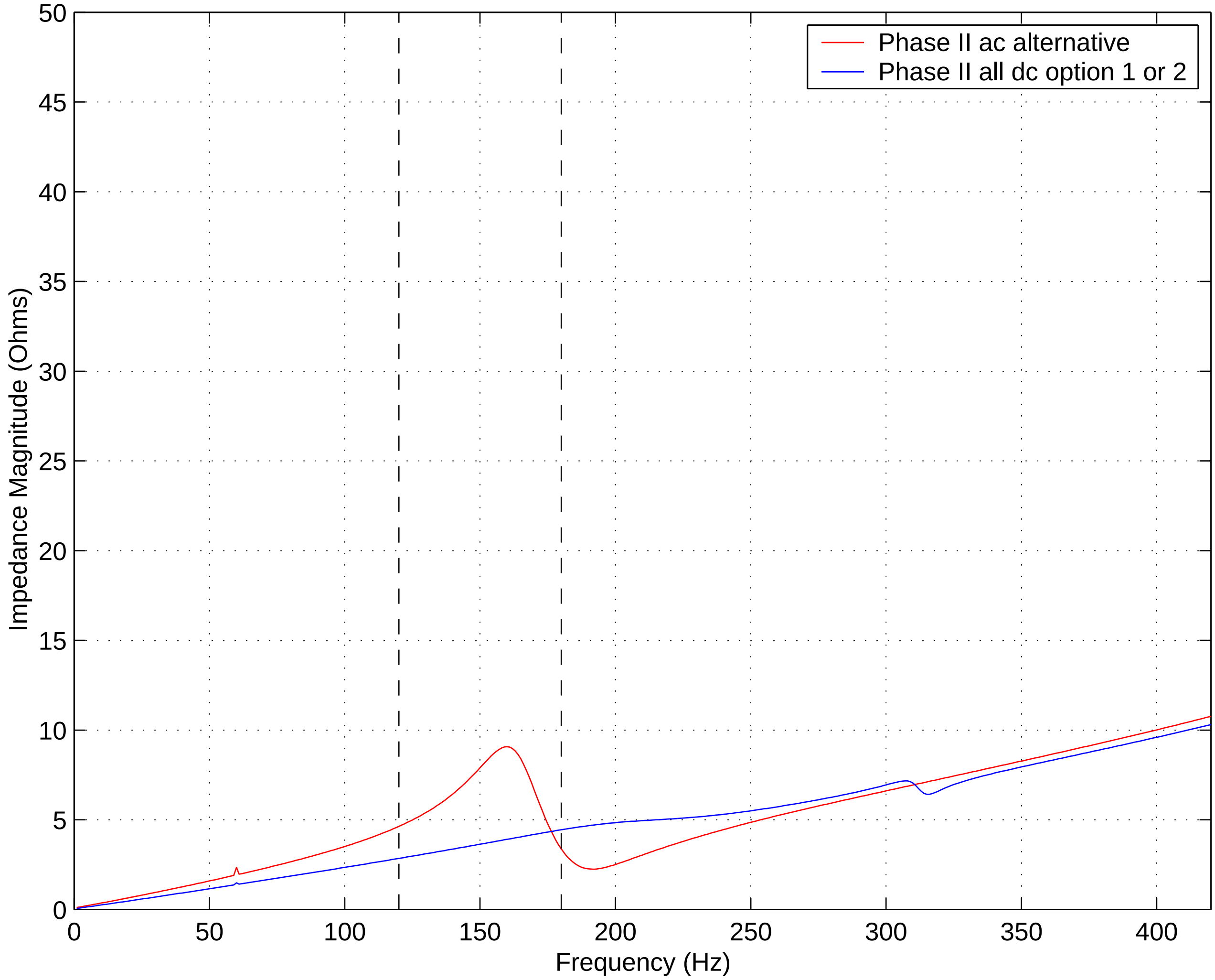


Figure D−3: Frequency Scan at Devon 345 kV
Phase II ac alternative
Impedance Magnitude (Ohms)
Frequency (Hz)
0
20
40
60
80
100
120
140
160
180
200
0
50
100
150
200
250
300
350
400

Figure D−4: Frequency Scan at Devon 115 kV



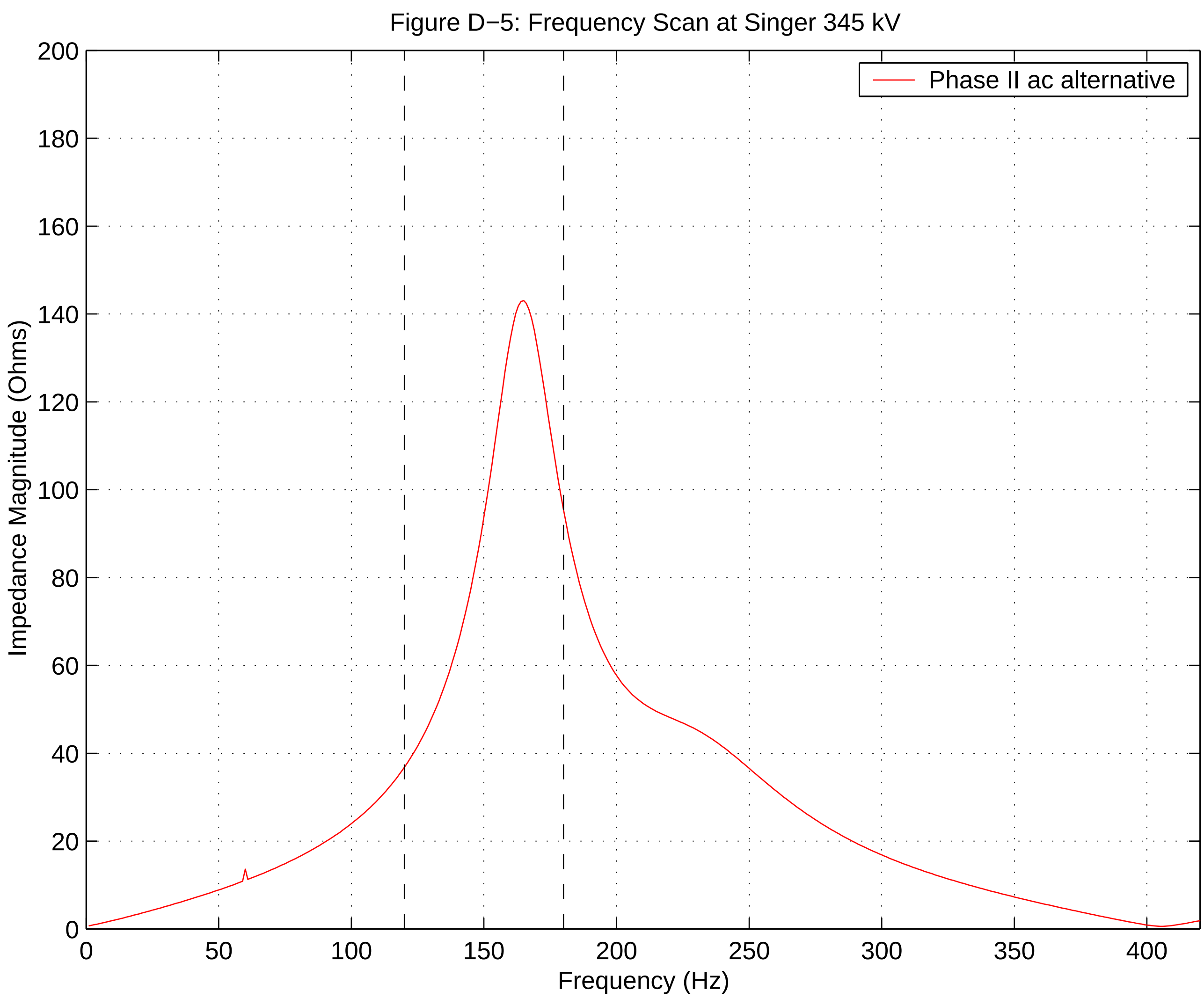


Figure D−5: Frequency Scan at Singer 345 kV
Phase II ac alternative
Impedance Magnitude (Ohms)
Frequency (Hz)
0
20
40
60
80
100
120
140
160
180
200
0
50
100
150
200
250
300
350
400

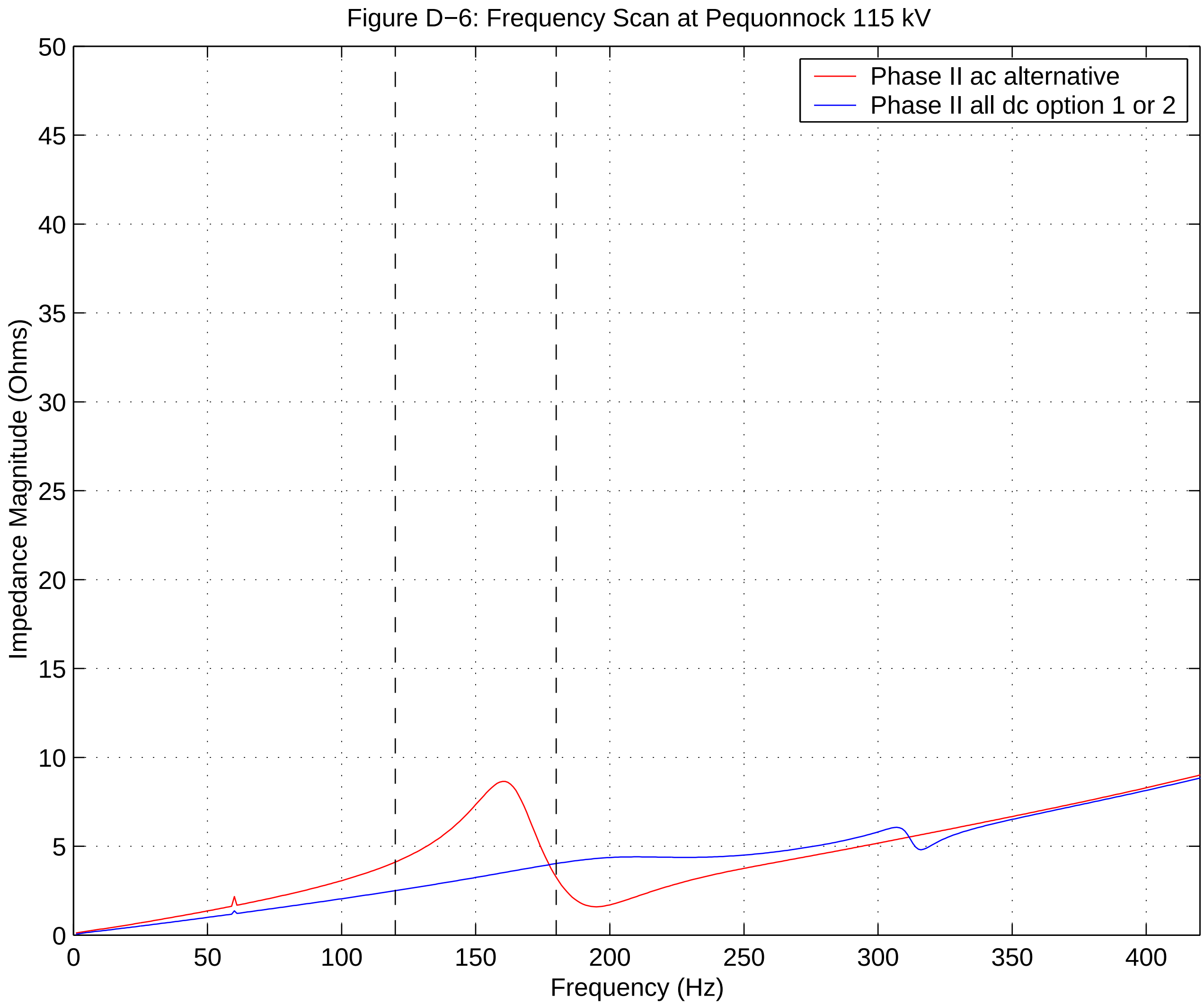


Figure D−6: Frequency Scan at Pequonnock 115 kV
Impedance Magnitude (Ohms)
Frequency (Hz)
Phase II ac alternative
Phase II all dc option 1 or 2
0
5
10
15
20
25
30
35
40
45
50
0
50
100
150
200
250
300
350
400

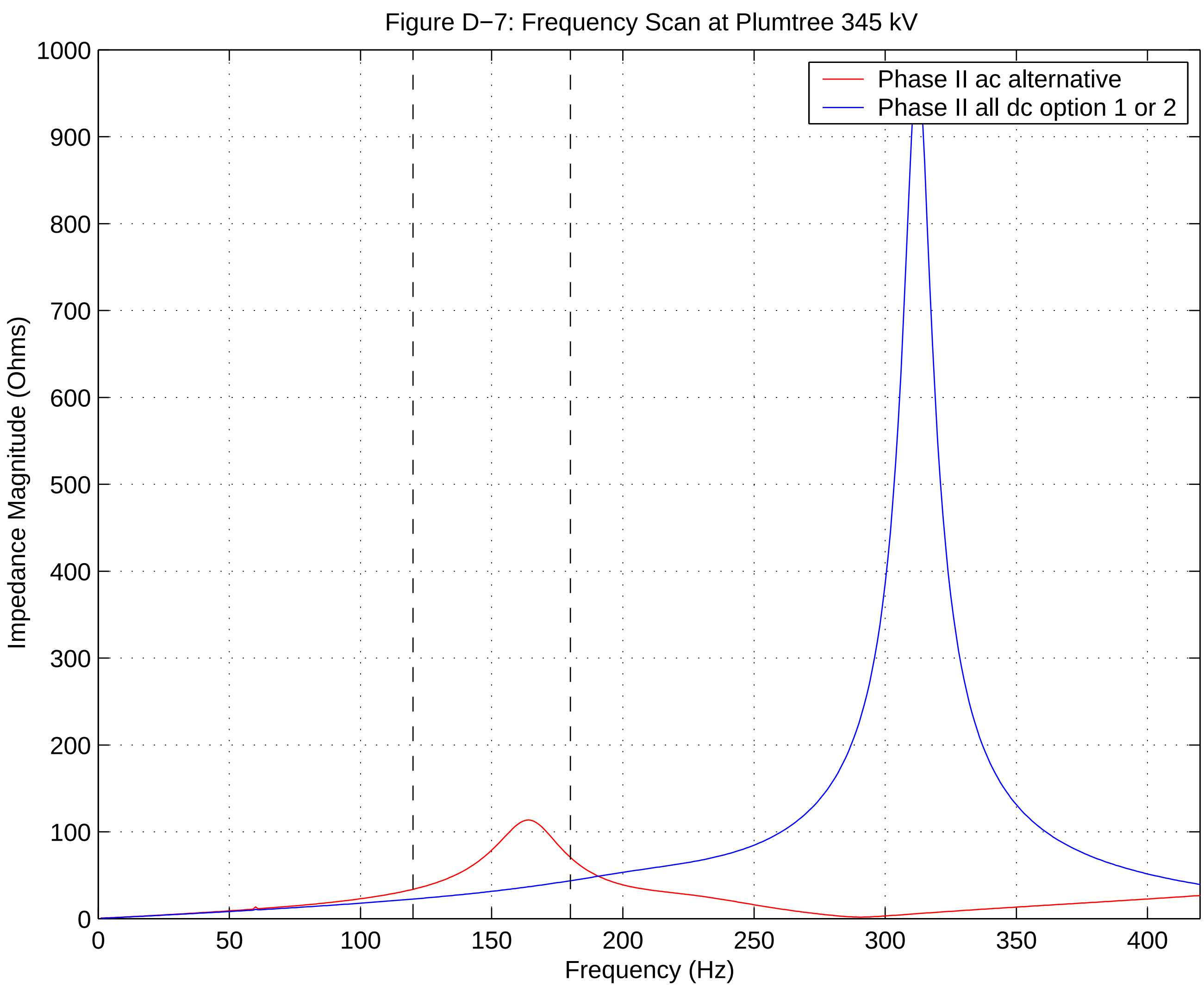


Figure D−7: Frequency Scan at Plumtree 345 kV
Phase II ac alternative
Phase II all dc option 1 or 2
Impedance Magnitude (Ohms)
Frequency (Hz)
0
100
200
300
400
500
600
700
800
900
1000
0
50
100
150
200
250
300
350
400

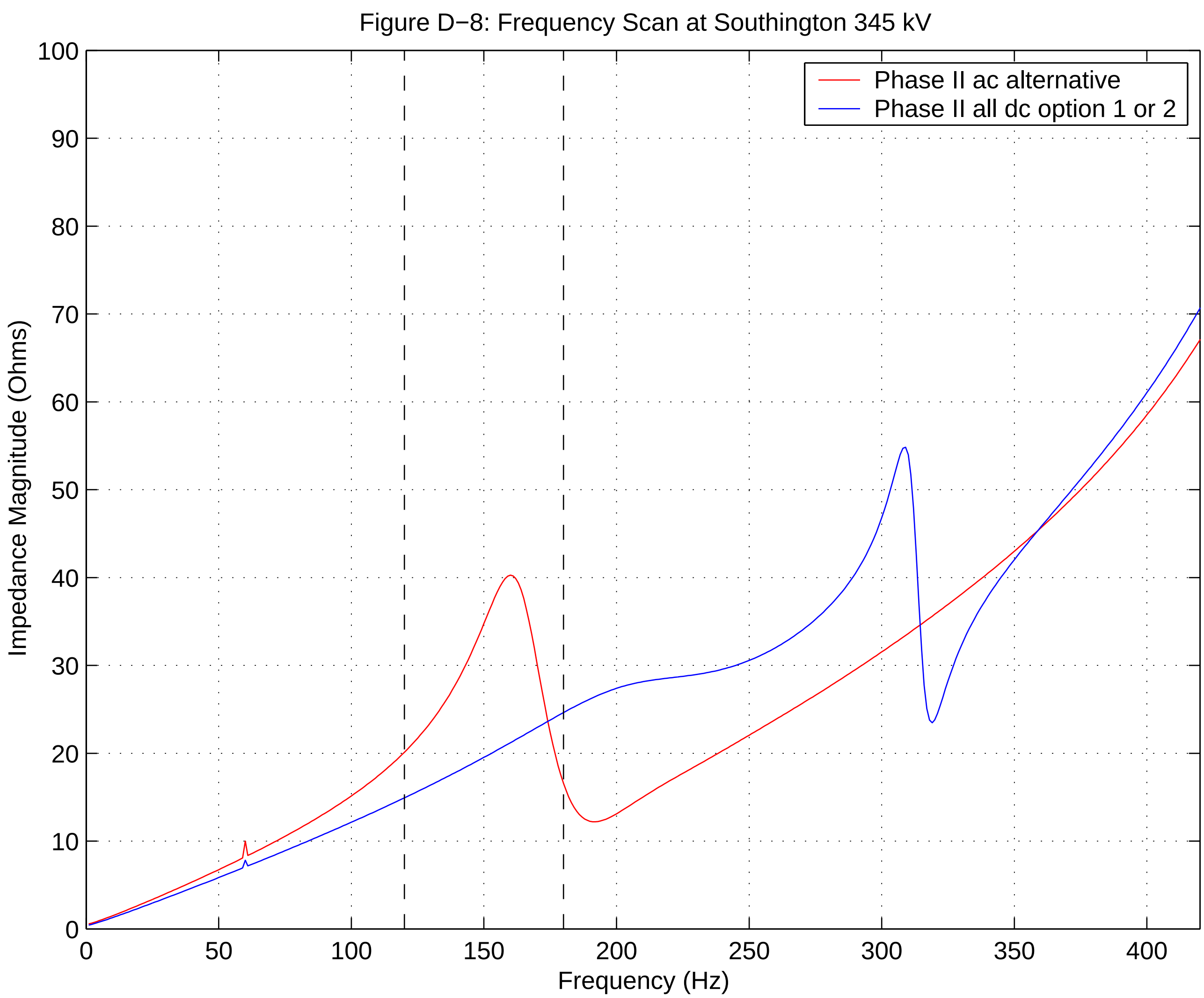


Figure D−8: Frequency Scan at Southington 345 kV
Phase II ac alternative
Phase II all dc option 1 or 2
Impedance Magnitude (Ohms)
Frequency (Hz)
0
10
20
30
40
50
60
70
80
90
100
0
50
100
150
200
250
300
350
400

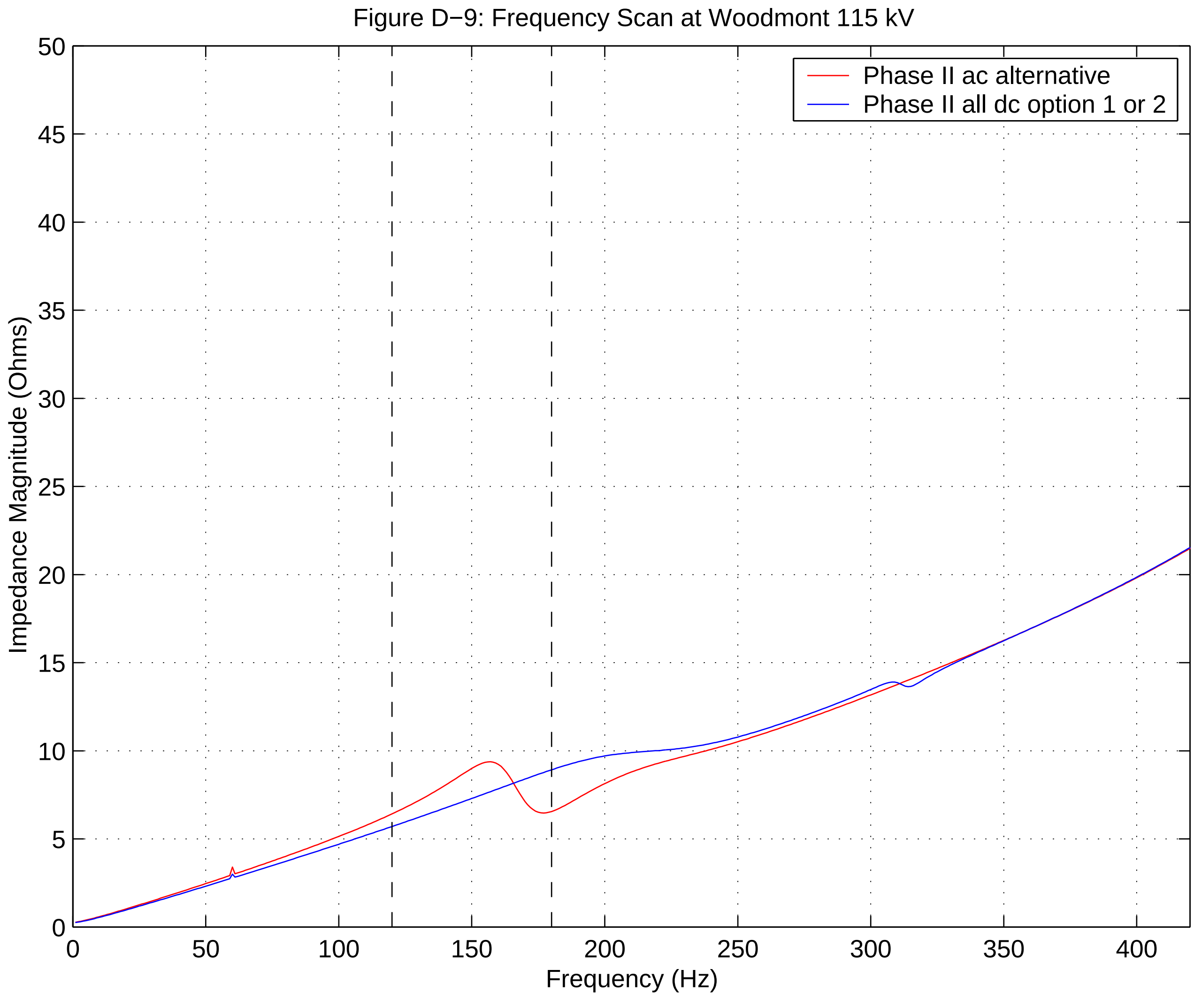


Figure D−9: Frequency Scan at Woodmont 115 kV
Phase II ac alternative
Phase II all dc option 1 or 2
Impedance Magnitude (Ohms)
Frequency (Hz)
0
5
10
15
20
25
30
35
40
45
50
0
50
100
150
200
250
300
350
400

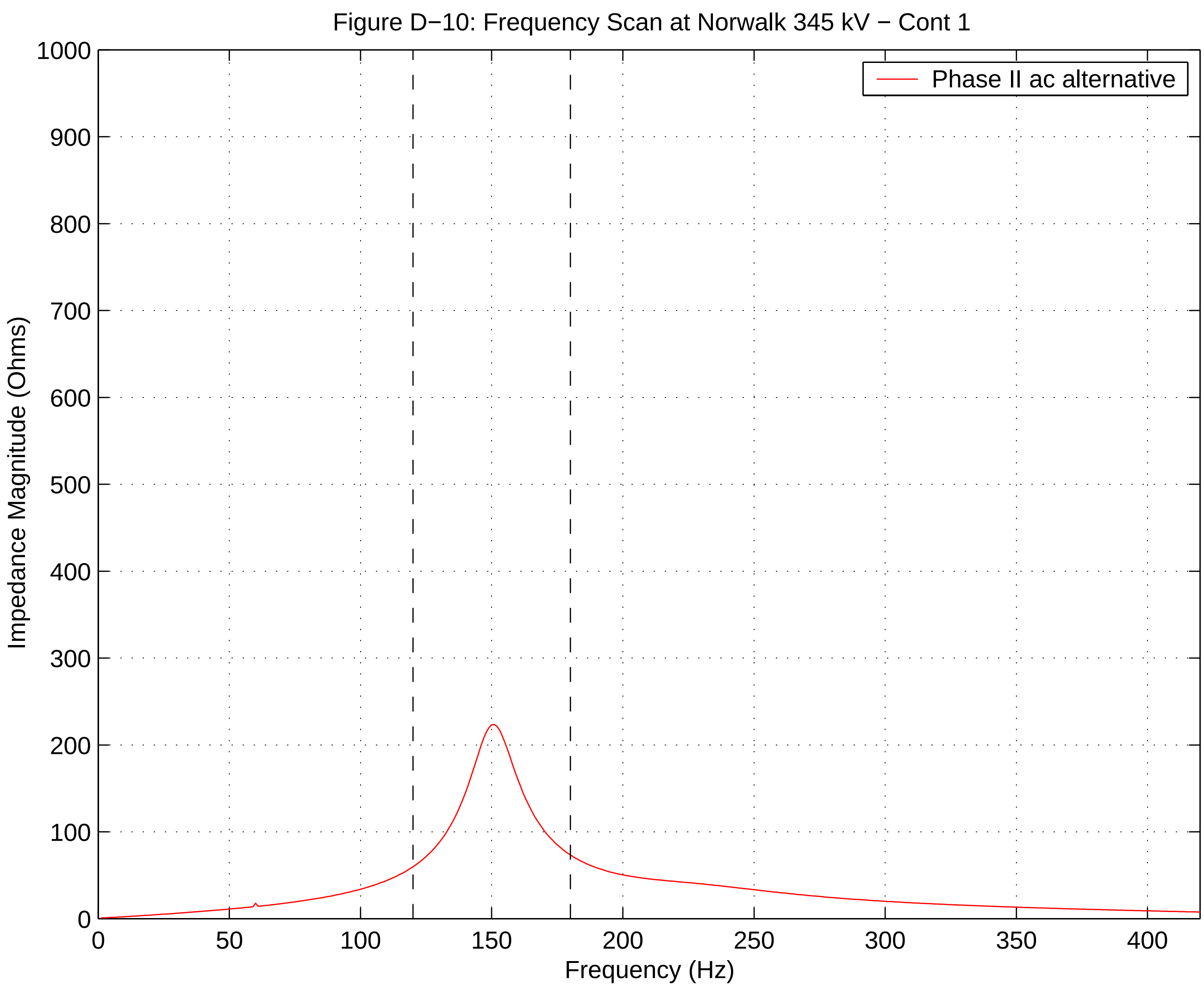


Figure D−10: Frequency Scan at Norwalk 345 kV − Cont 1
Phase II ac alternative
Impedance Magnitude (Ohms)
Frequency (Hz)
0
100
200
300
400
500
600
700
800
900
1000
50
150
250
350

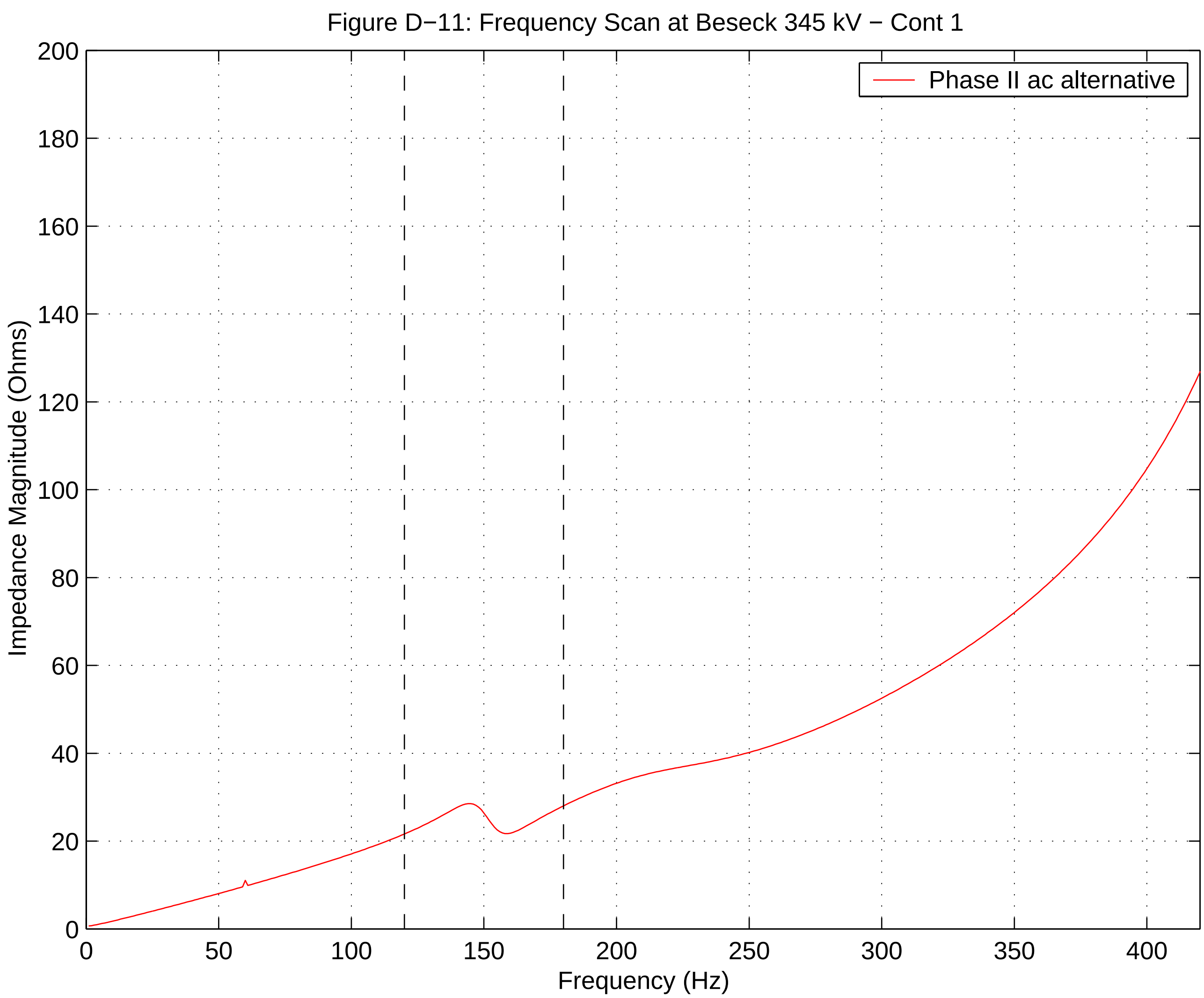


Figure D−11: Frequency Scan at Beseck 345 kV − Cont 1
Phase II ac alternative
Impedance Magnitude (Ohms)
Frequency (Hz)
0
20
40
60
80
100
120
140
160
180
200
0
50
100
150
200
250
300
350
400

Figure D−12: Frequency Scan at Devon 345 kV − Cont 1

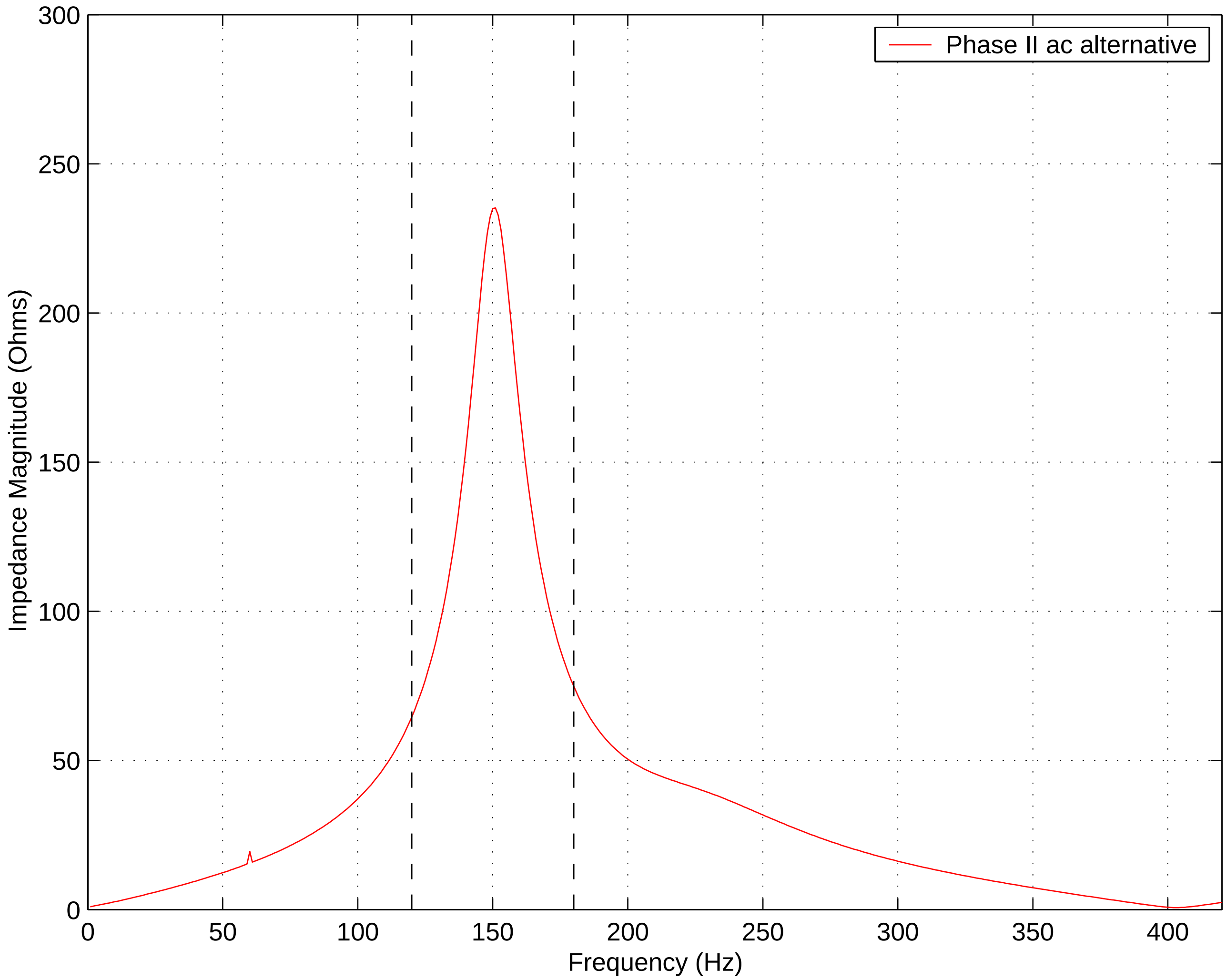


Figure D−13: Frequency Scan at Devon 115 kV − Cont 1

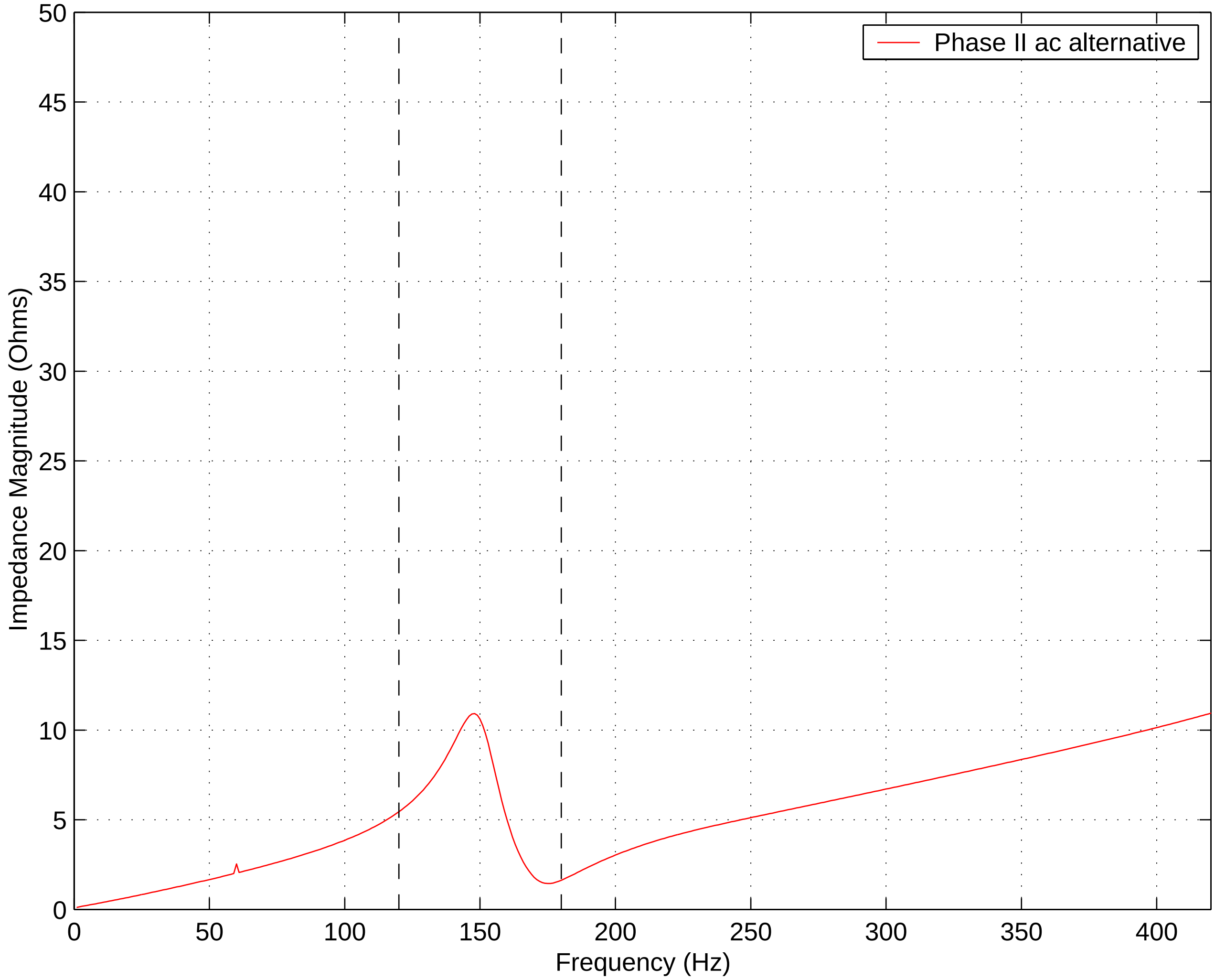


Figure D−14: Frequency Scan at Singer 345 kV − Cont 1

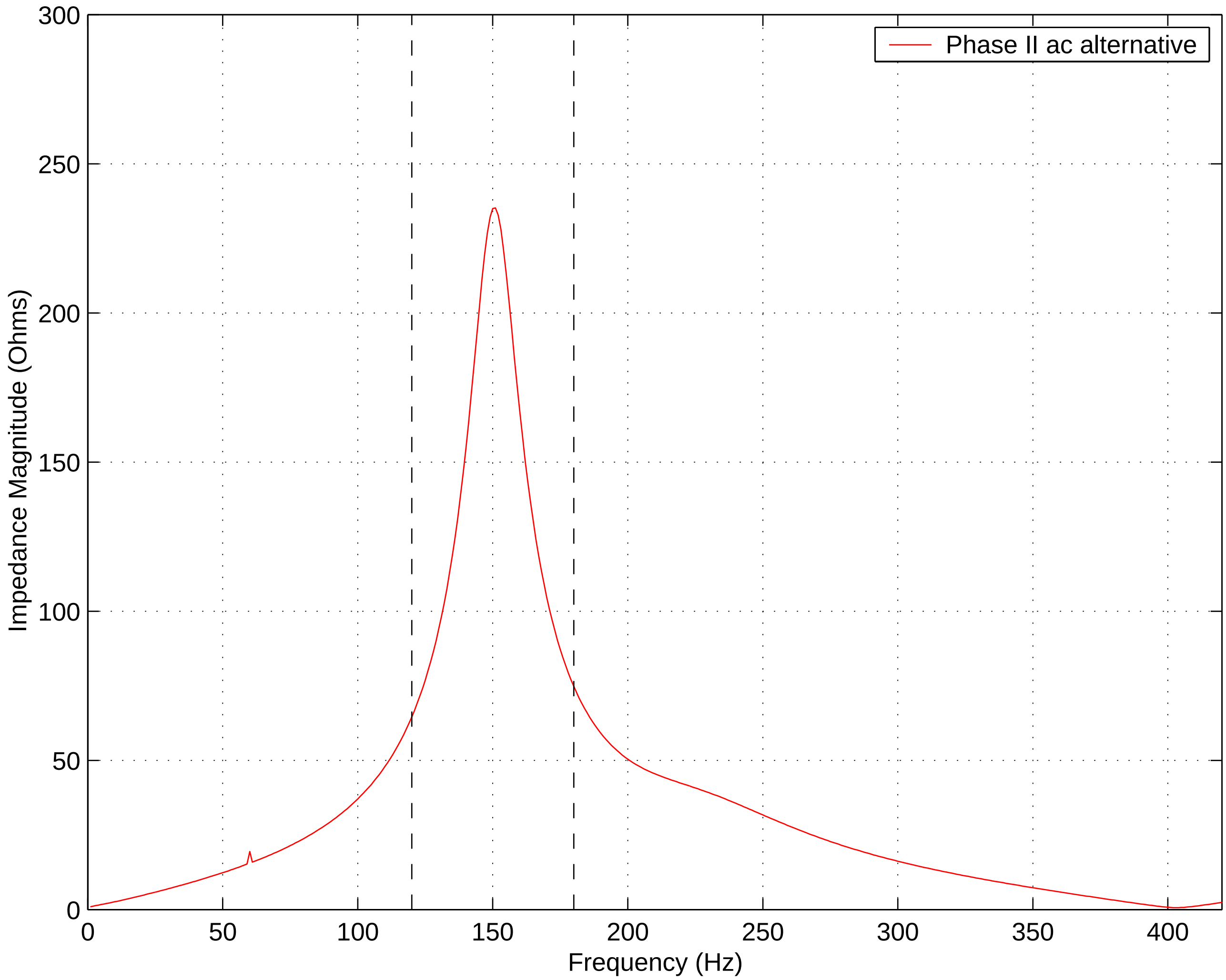
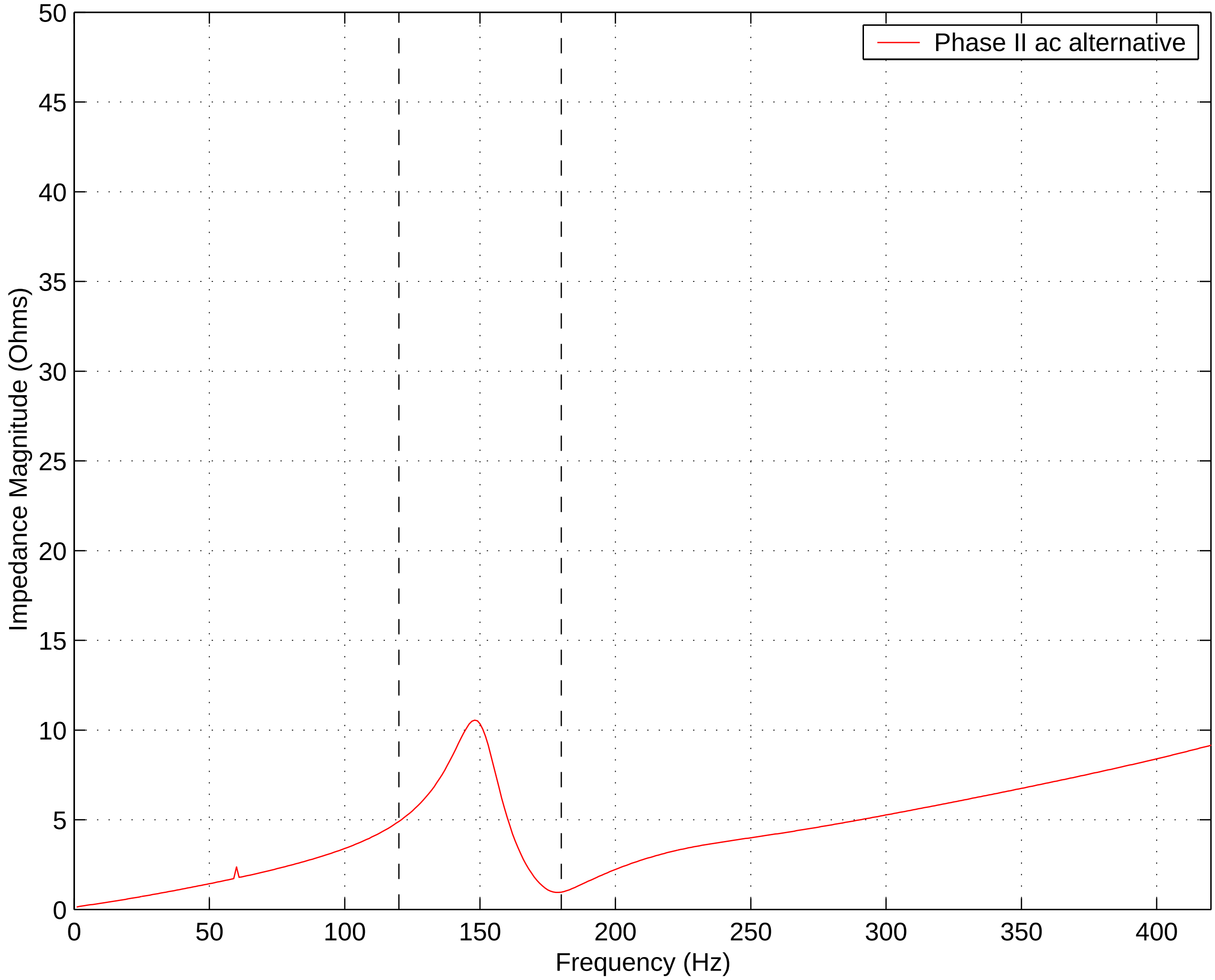


Figure D−15: Frequency Scan at Pequonnock 115 kV − Cont 1



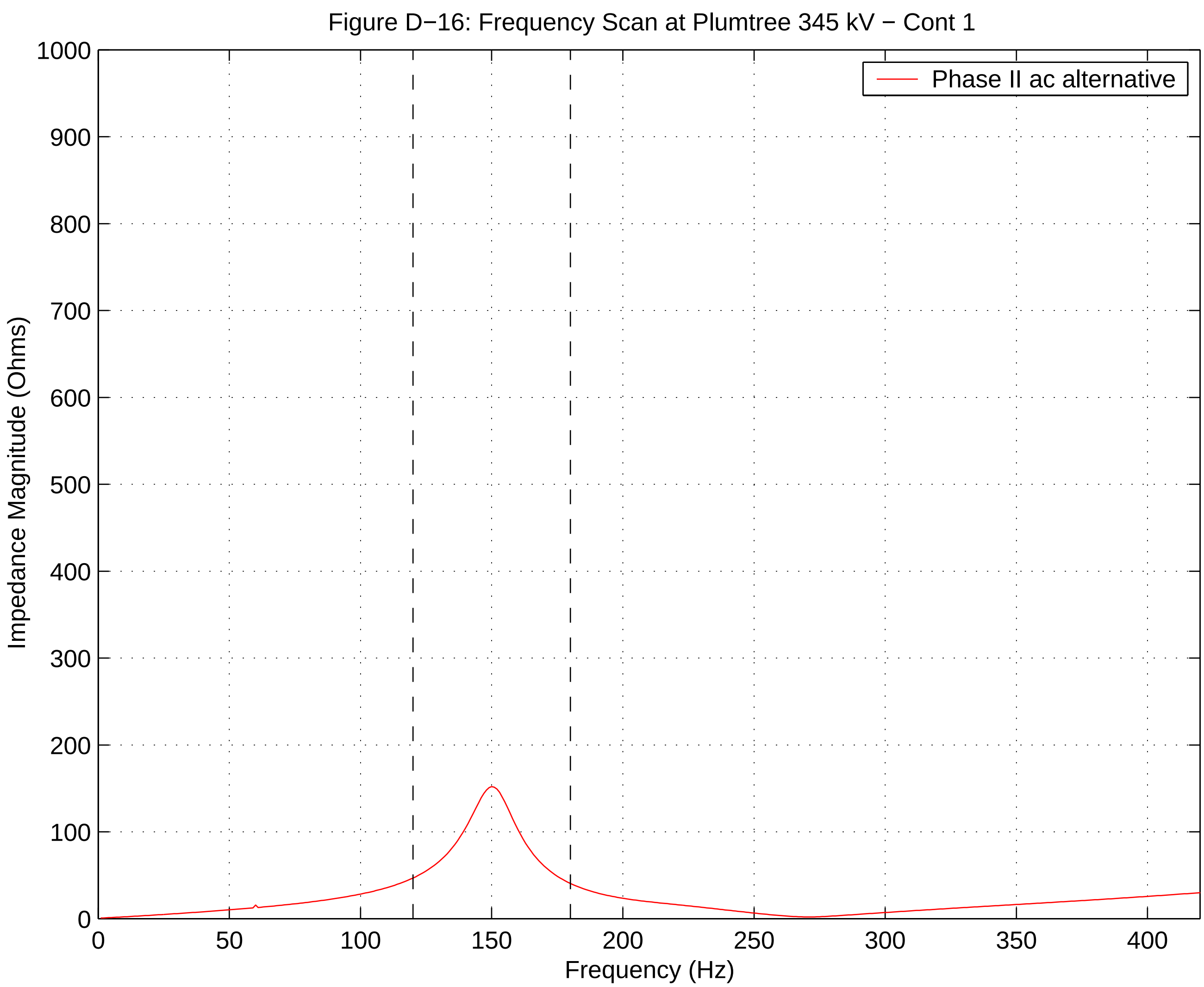


Figure D−16: Frequency Scan at Plumtree 345 kV − Cont 1
Phase II ac alternative
Impedance Magnitude (Ohms)
Frequency (Hz)
0
100
200
300
400
500
600
700
800
900
1000
50
150
250
350

Figure D−17: Frequency Scan at Southington 345 kV − Cont 1

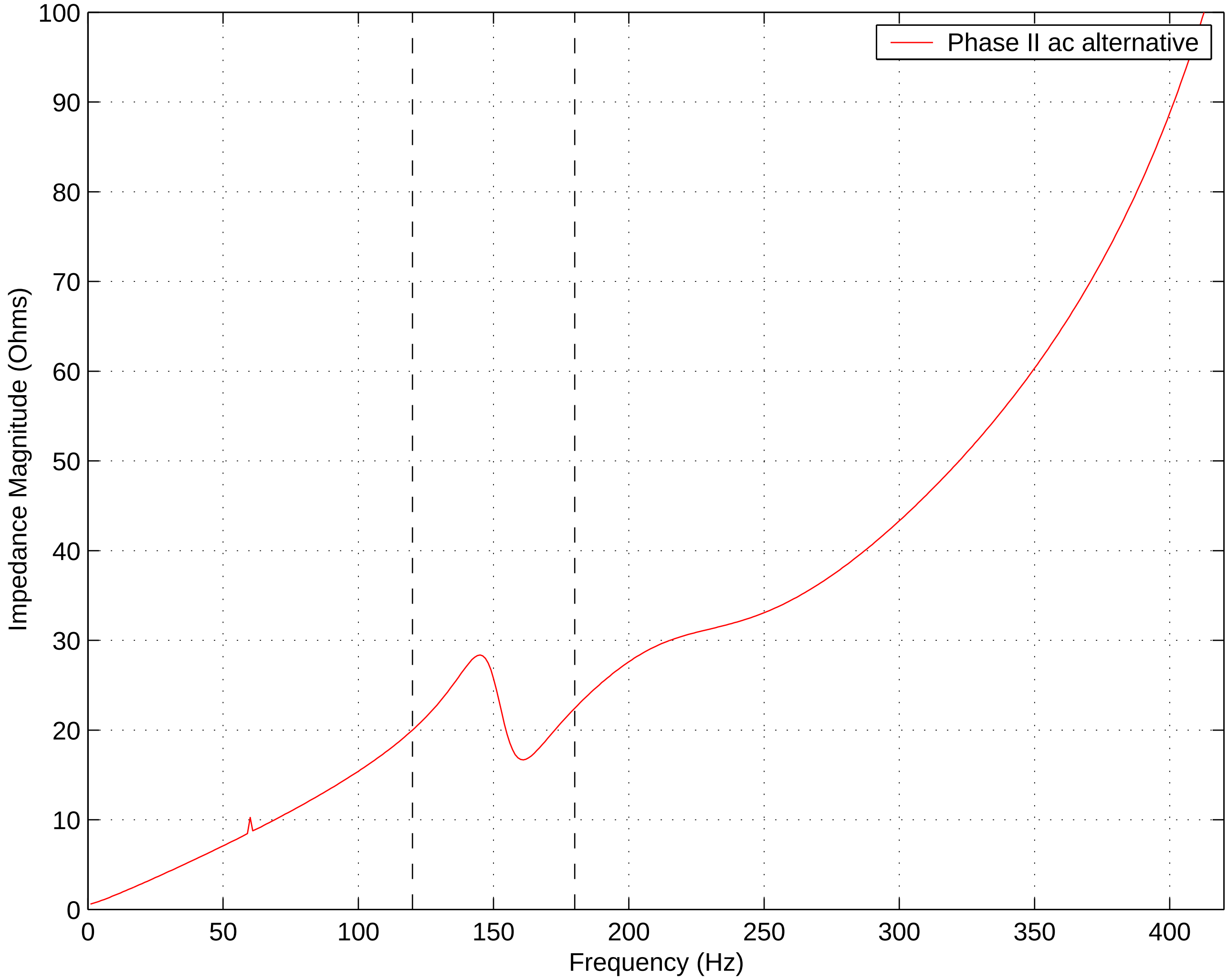


Figure D−18: Frequency Scan at Woodmont 115 kV − Cont 1

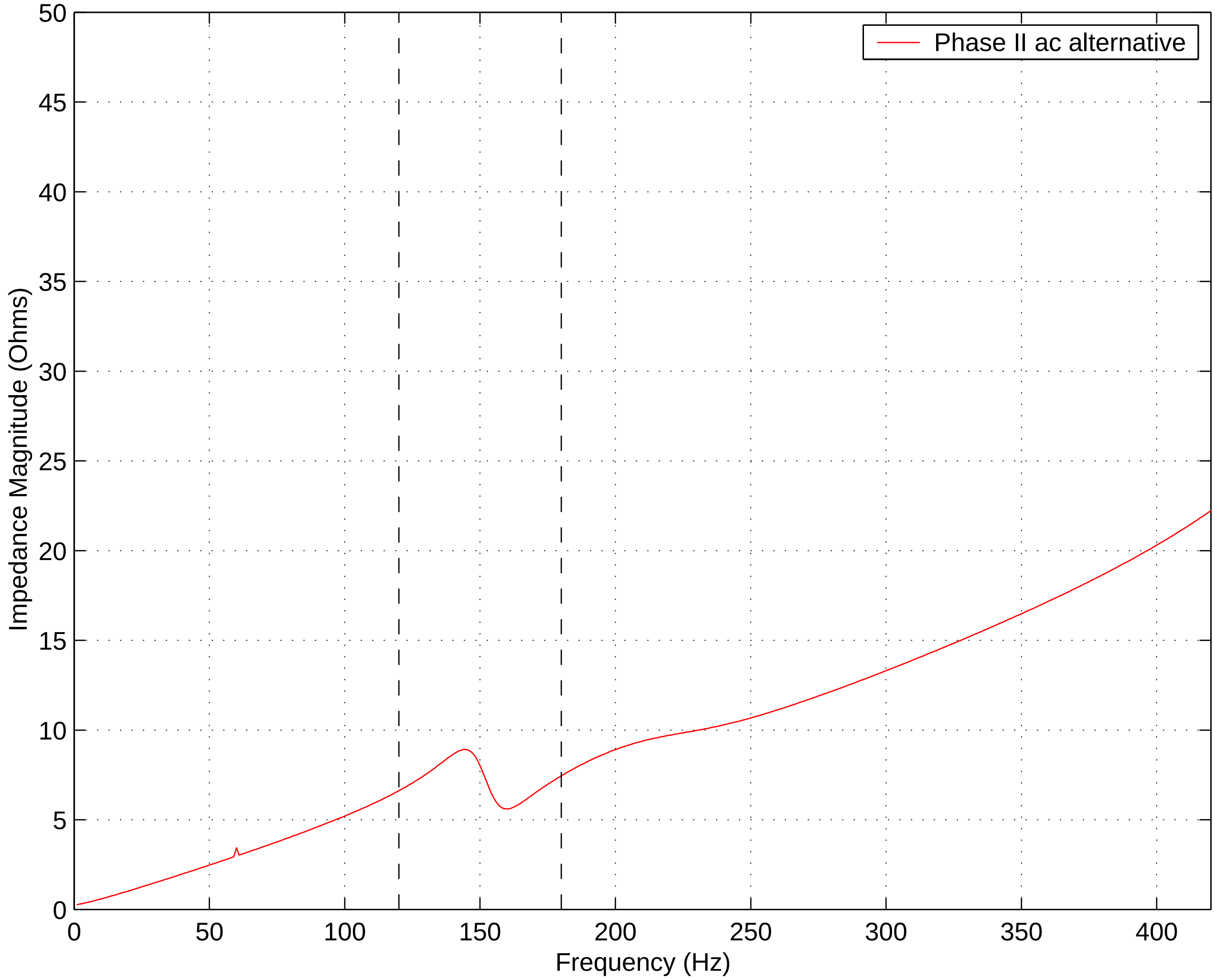
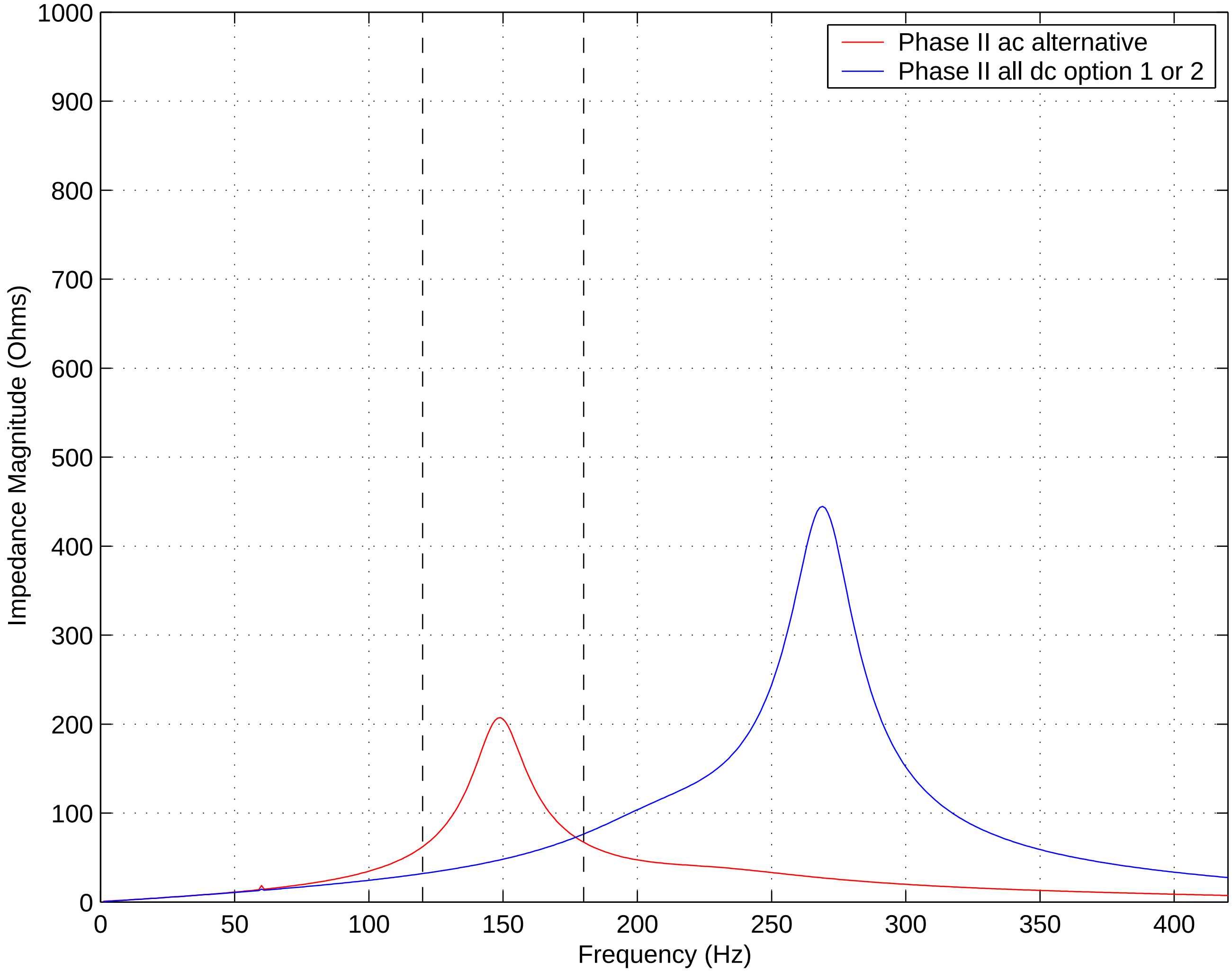


Figure D−19: Frequency Scan at Norwalk 345 kV − Cont 2



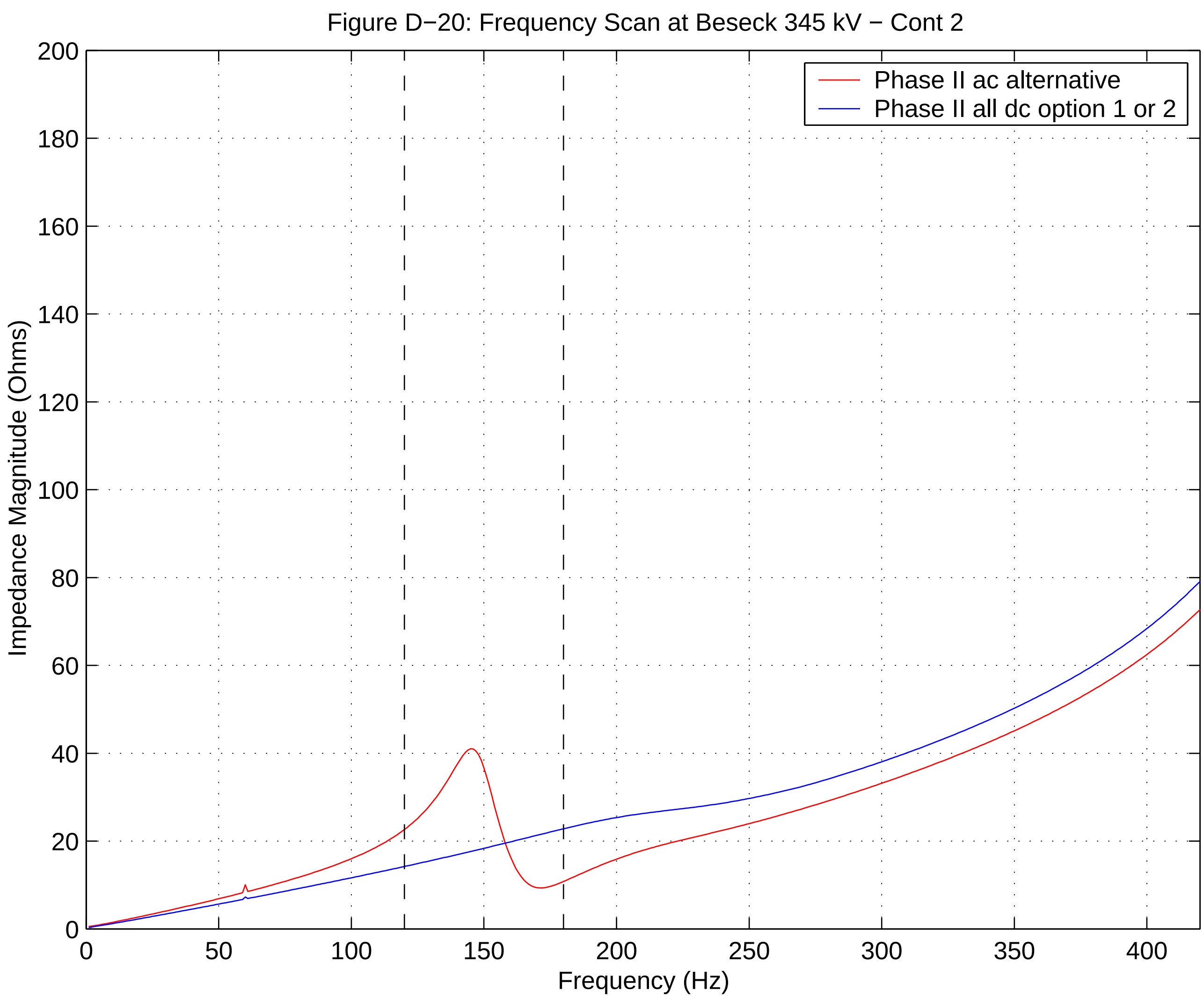
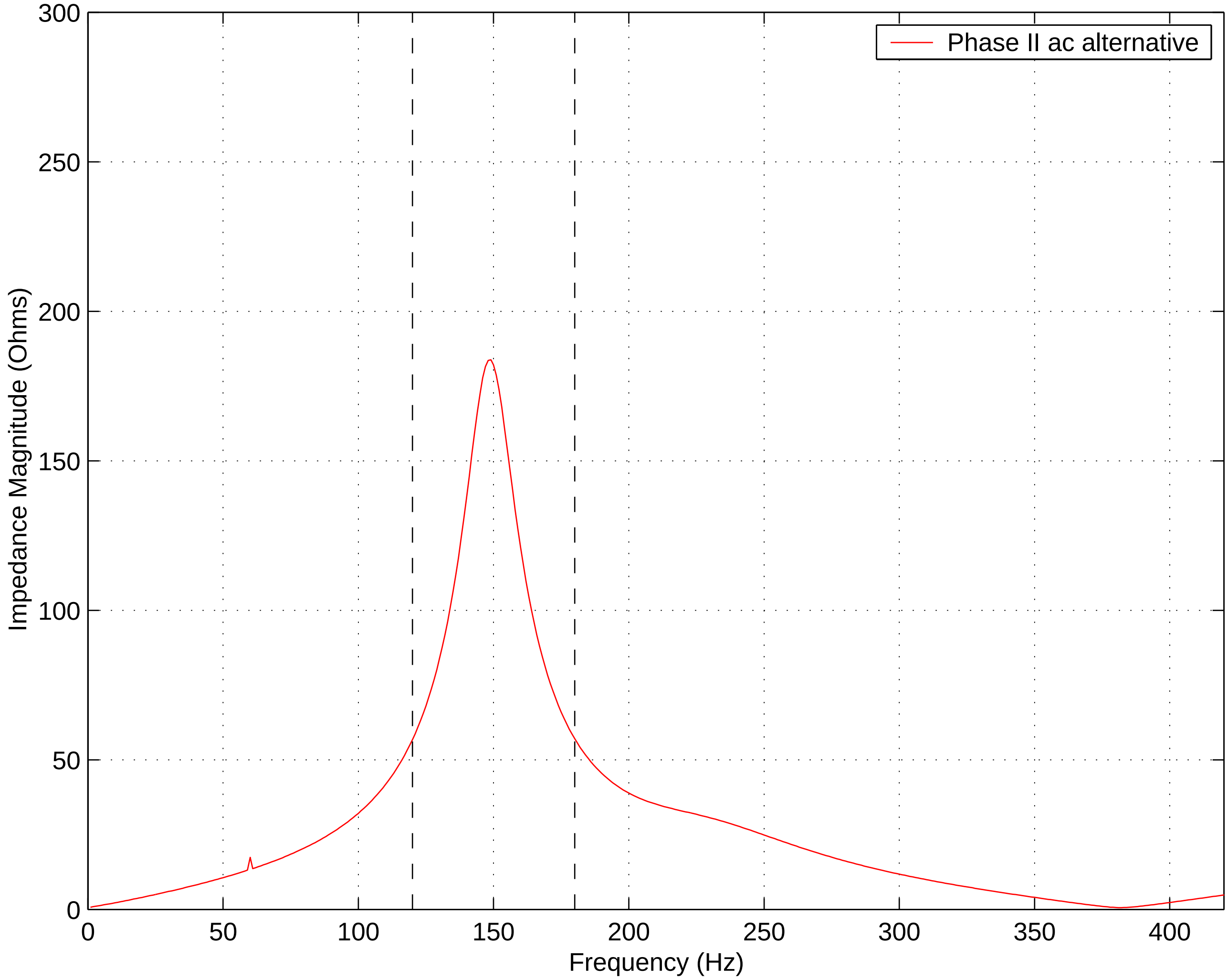


Figure D−20: Frequency Scan at Beseck 345 kV − Cont 2
Phase II ac alternative
Phase II all dc option 1 or 2
Impedance Magnitude (Ohms)
Frequency (Hz)
0
20
40
60
80
100
120
140
160
180
200
0
50
100
150
200
250
300
350
400

Figure D−21: Frequency Scan at Devon 345 kV − Cont 2



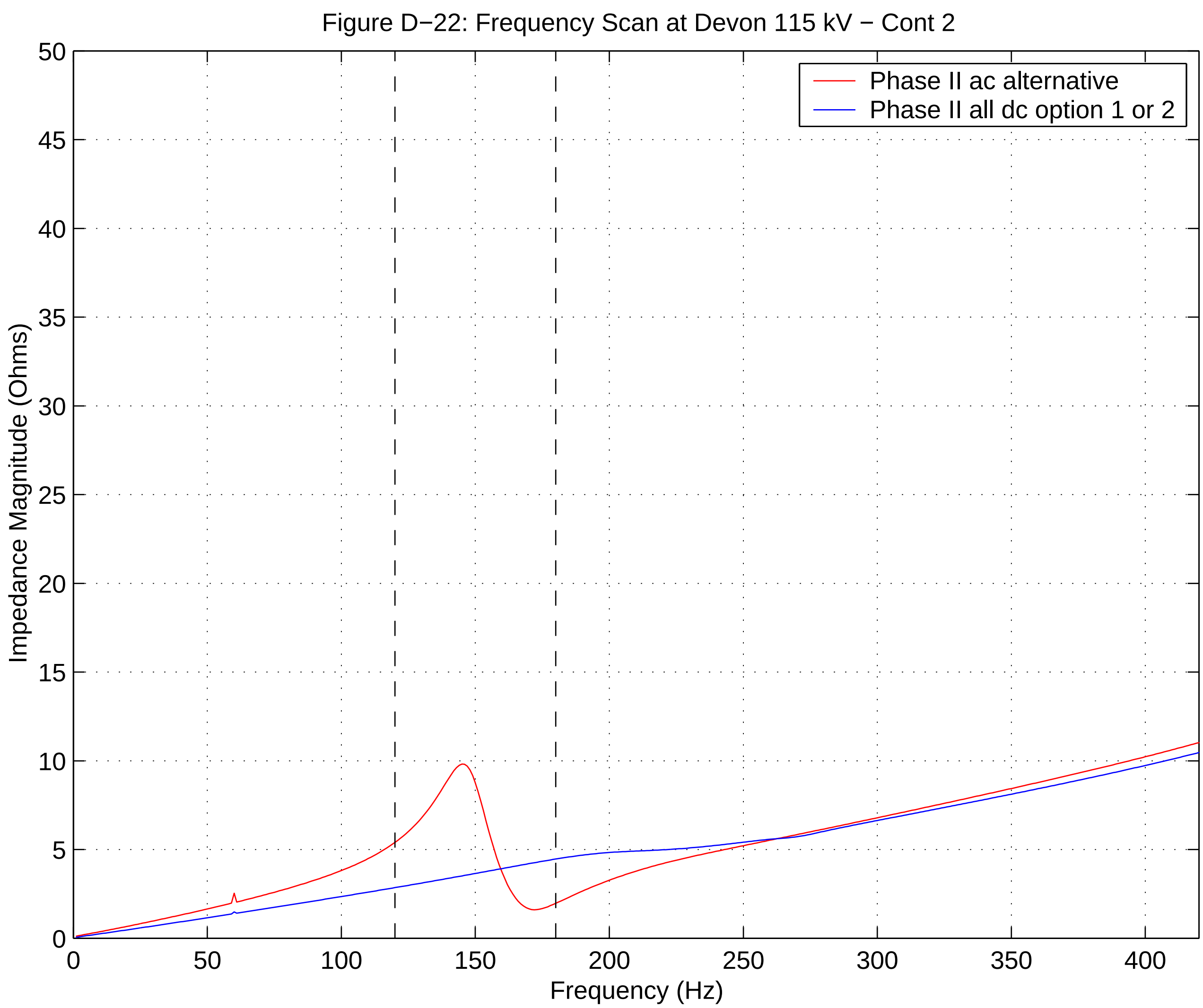
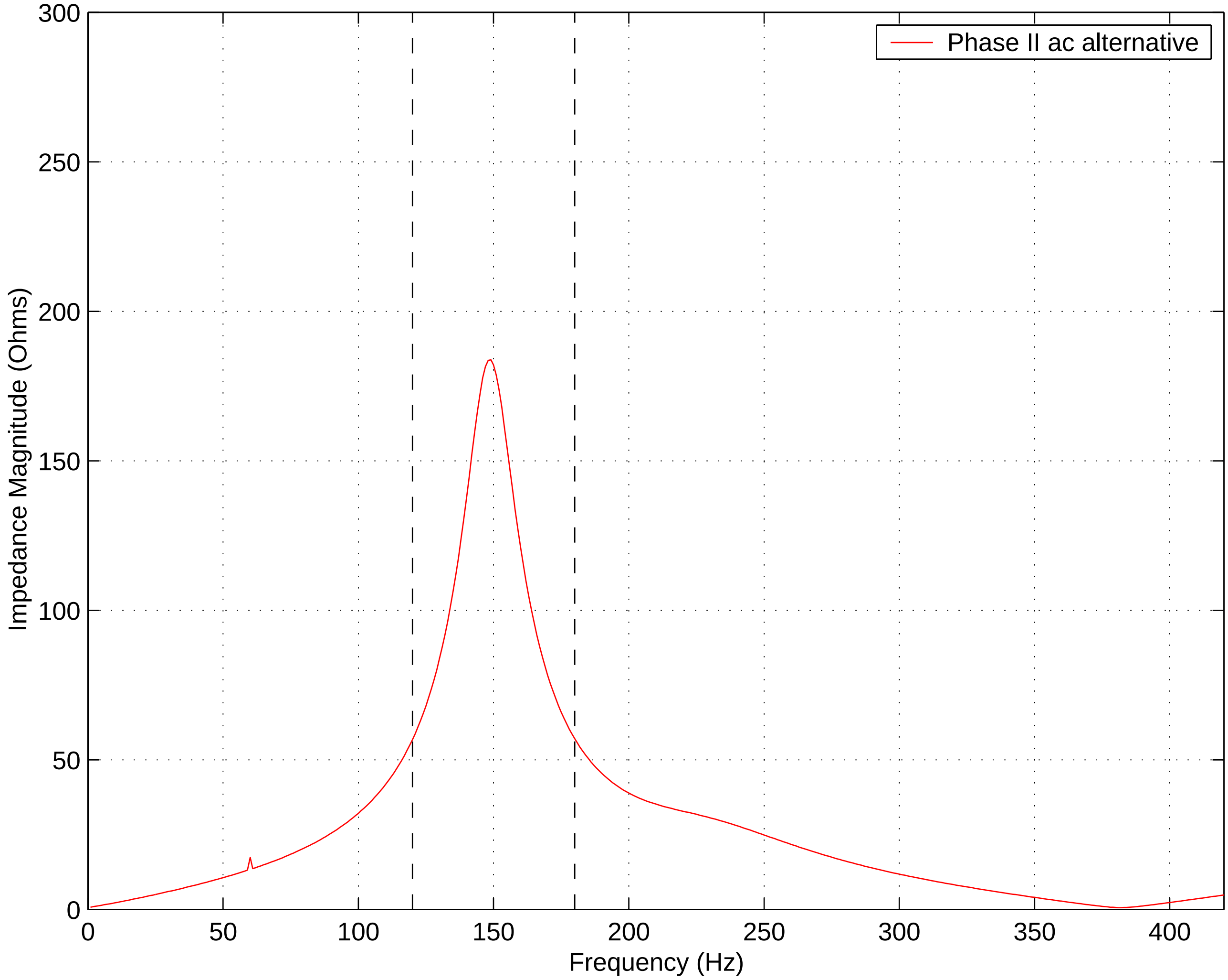


Figure D−22: Frequency Scan at Devon 115 kV − Cont 2
Phase II ac alternative
Phase II all dc option 1 or 2
Impedance Magnitude (Ohms)
Frequency (Hz)
0
5
10
15
20
25
30
35
40
45
50
0
50
100
150
200
250
300
350
400

Figure D−23: Frequency Scan at Singer 345 kV − Cont 2



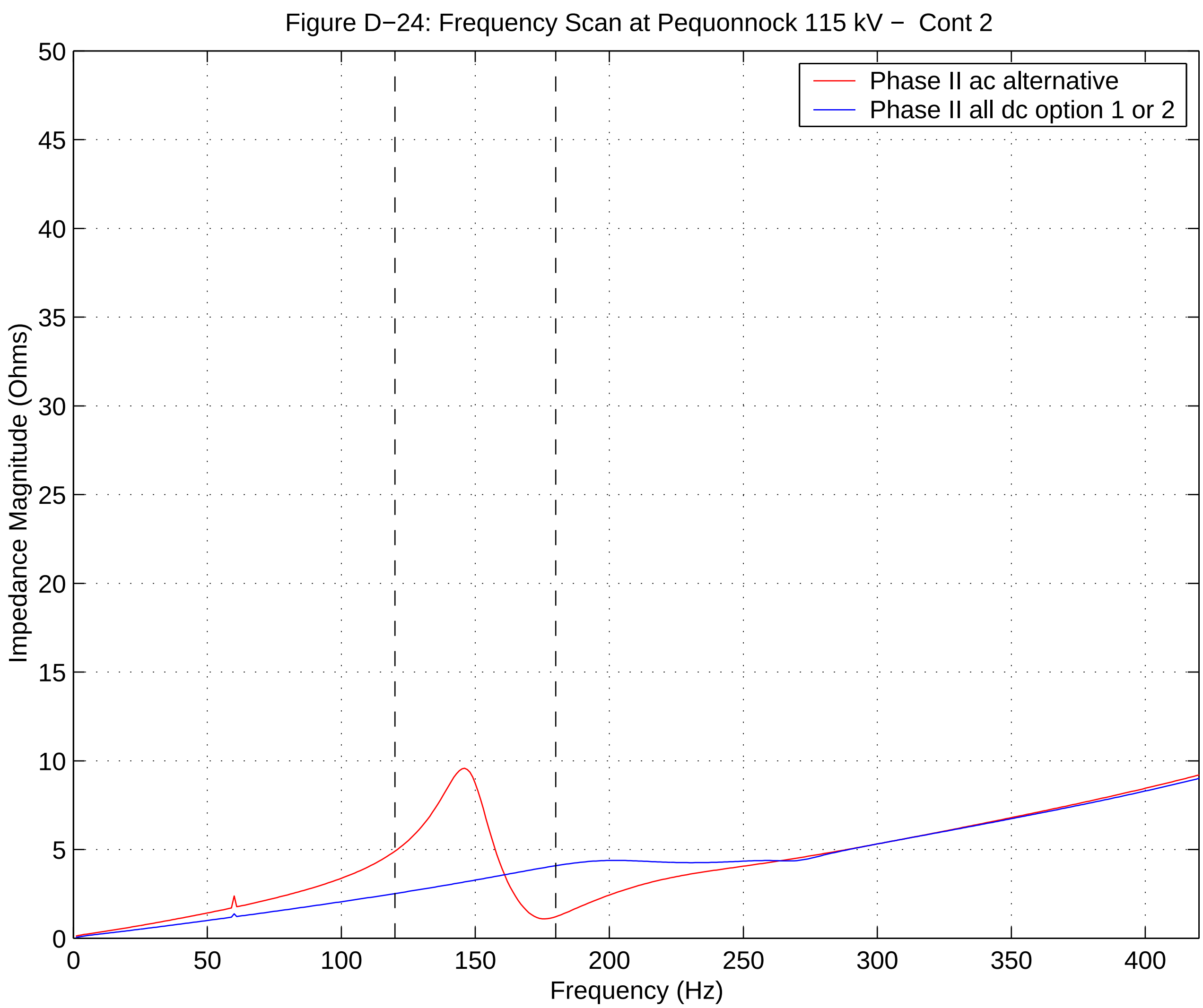


Figure D−24: Frequency Scan at Pequonnock 115 kV − Cont 2
Phase II ac alternative
Phase II all dc option 1 or 2
Impedance Magnitude (Ohms)
Frequency (Hz)
0
5
10
15
20
25
30
35
40
45
50
0
50
100
150
200
250
300
350
400

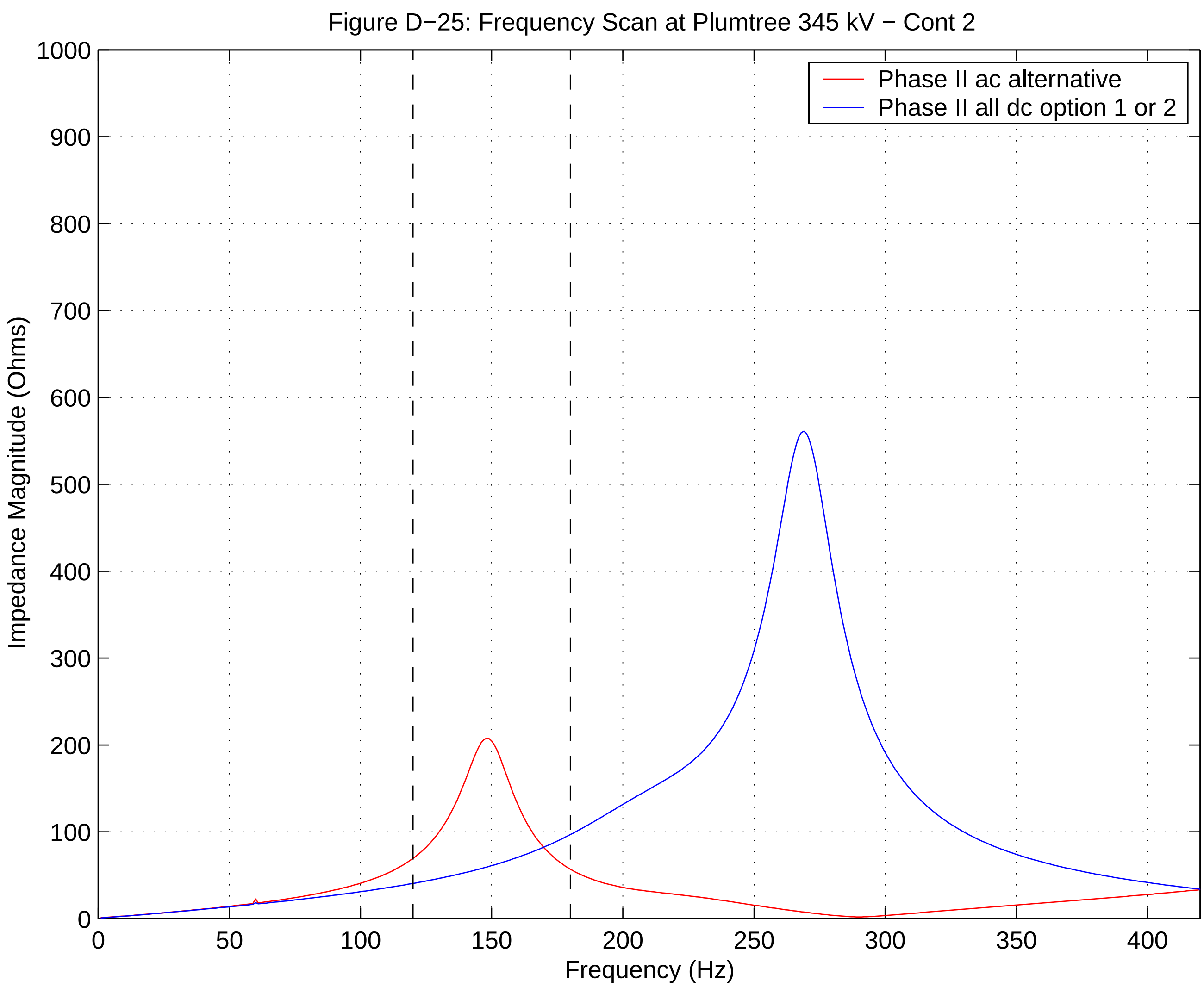
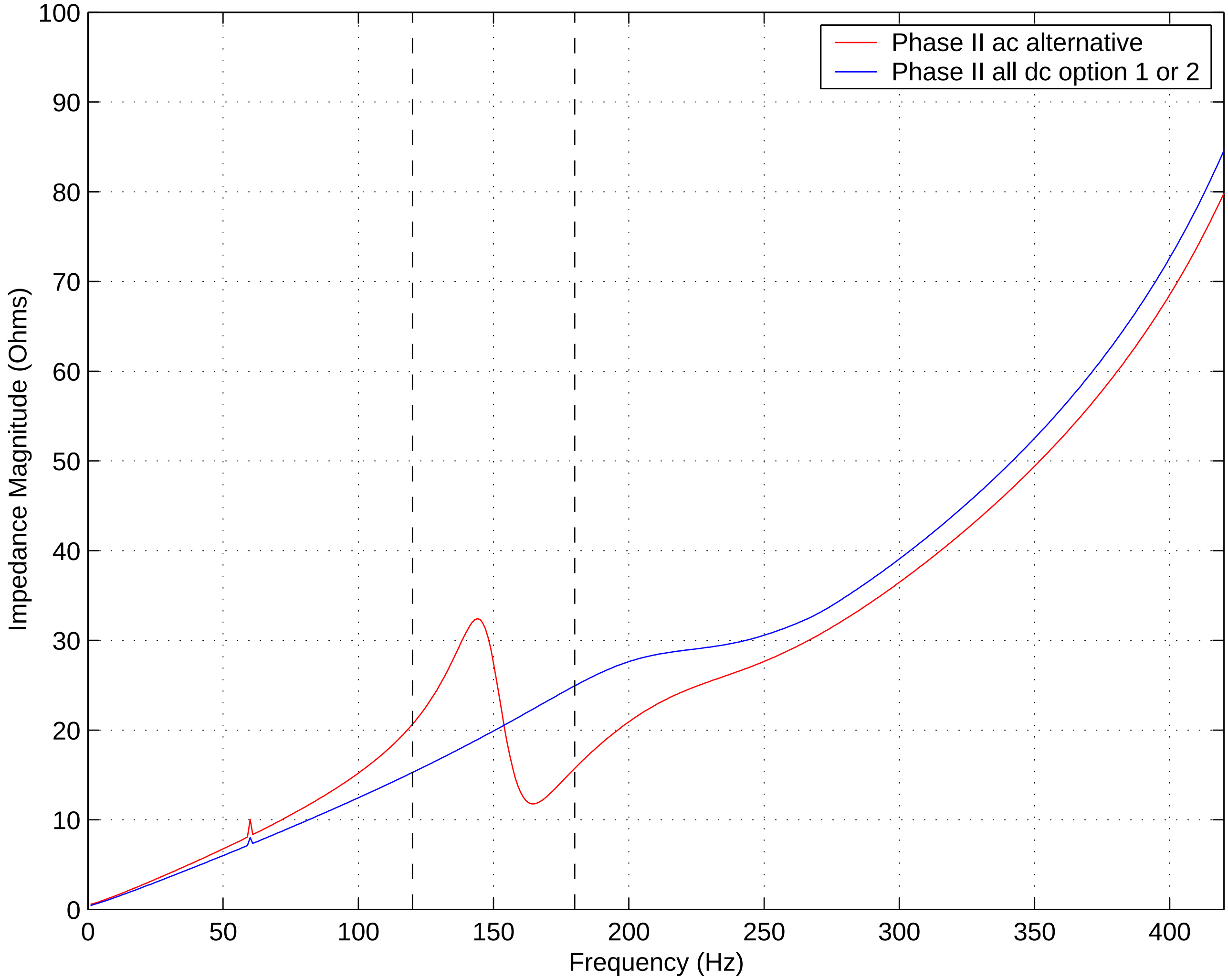


Figure D−25: Frequency Scan at Plumtree 345 kV − Cont 2
Phase II ac alternative
Phase II all dc option 1 or 2
Impedance Magnitude (Ohms)
Frequency (Hz)
0
100
200
300
400
500
600
700
800
900
1000
0
50
100
150
200
250
300
350
400

Figure D−26: Frequency Scan at Southington 345 kV − Cont 2



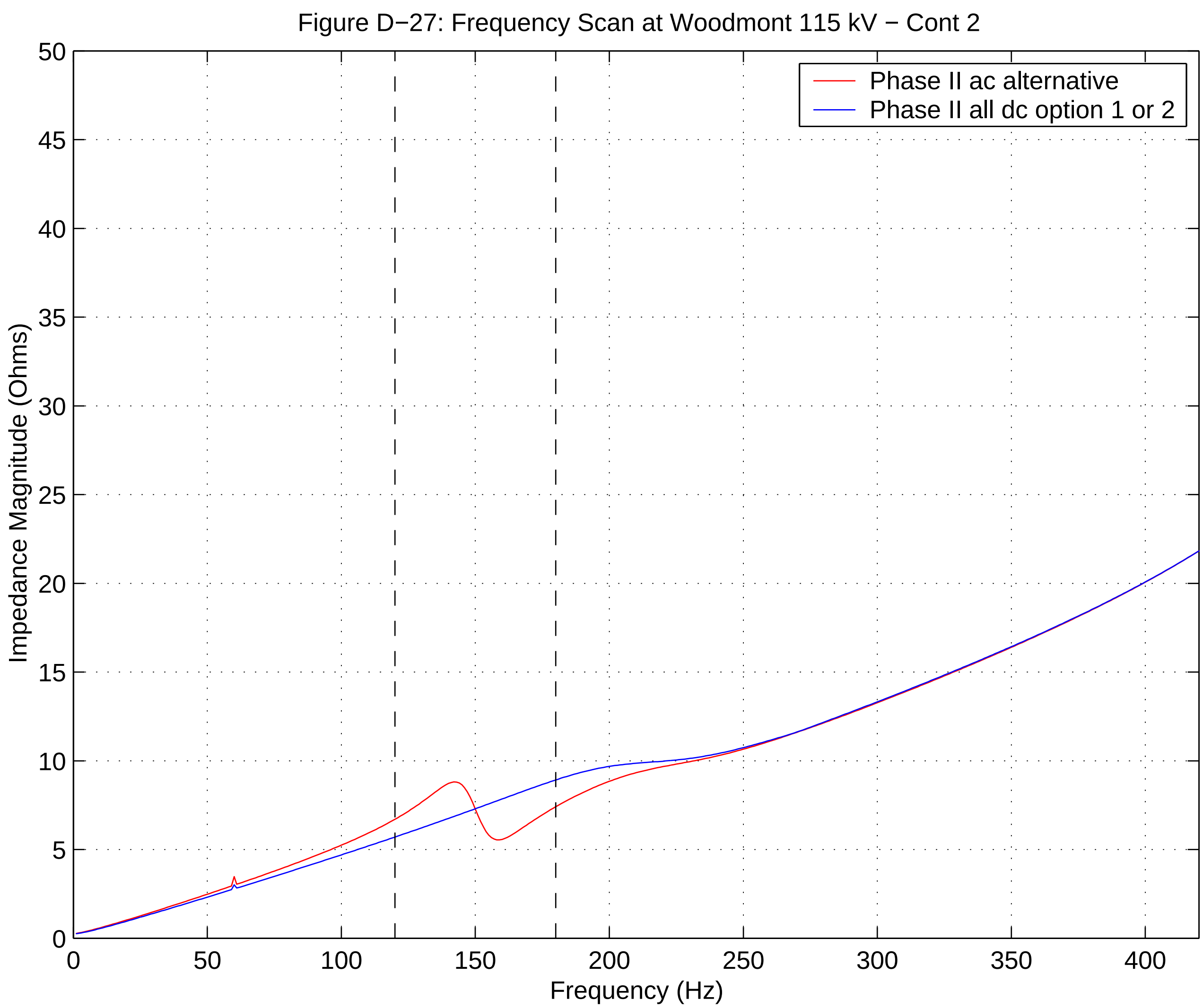


Figure D−27: Frequency Scan at Woodmont 115 kV − Cont 2
Phase II ac alternative
Phase II all dc option 1 or 2
Impedance Magnitude (Ohms)
Frequency (Hz)
0
5
10
15
20
25
30
35
40
45
50
0
50
100
150
200
250
300
350
400

Figure D−28: Frequency Scan at Norwalk 345 kV − Cont 3

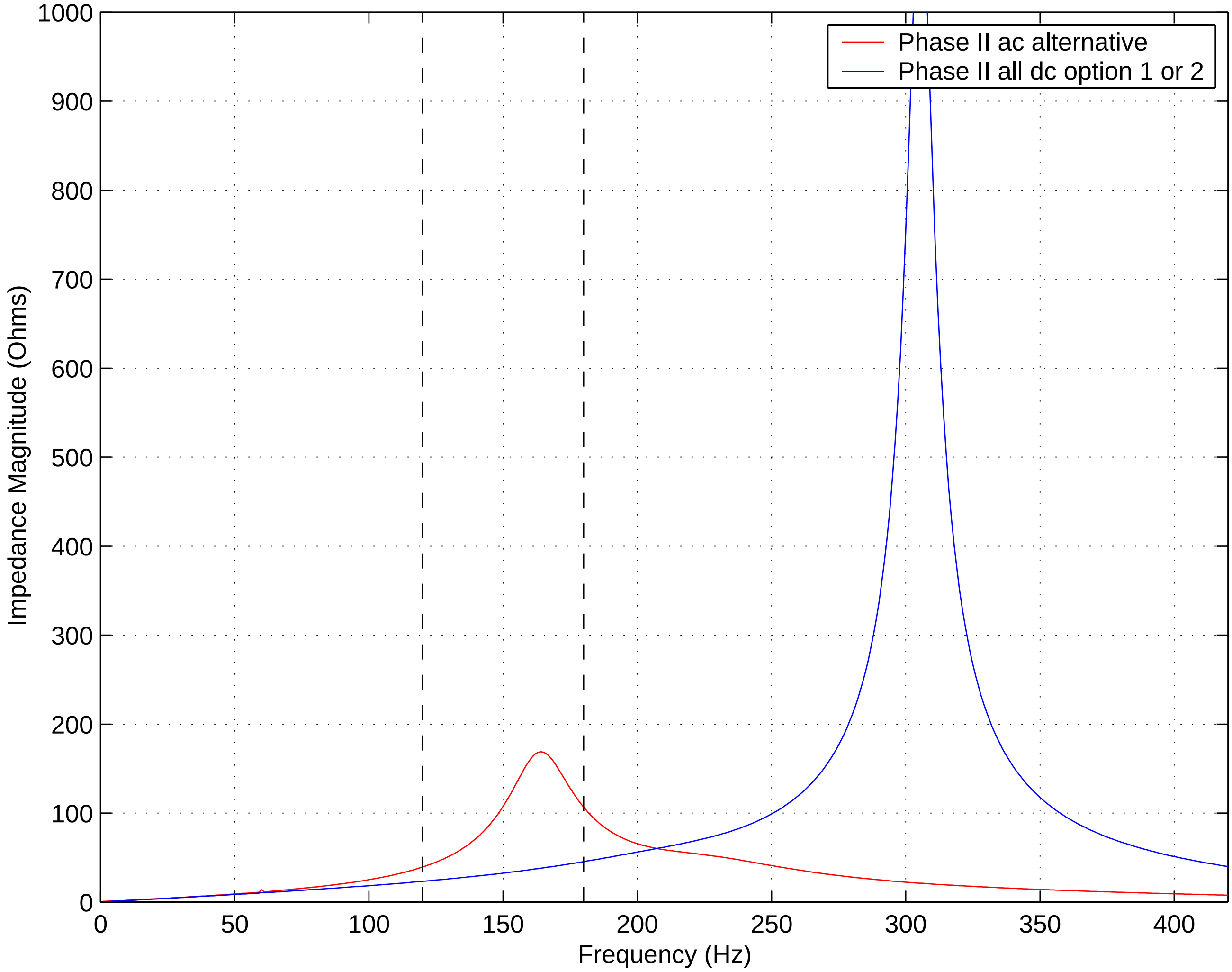


Figure D−29: Frequency Scan at Beseck 345 kV − Cont 3

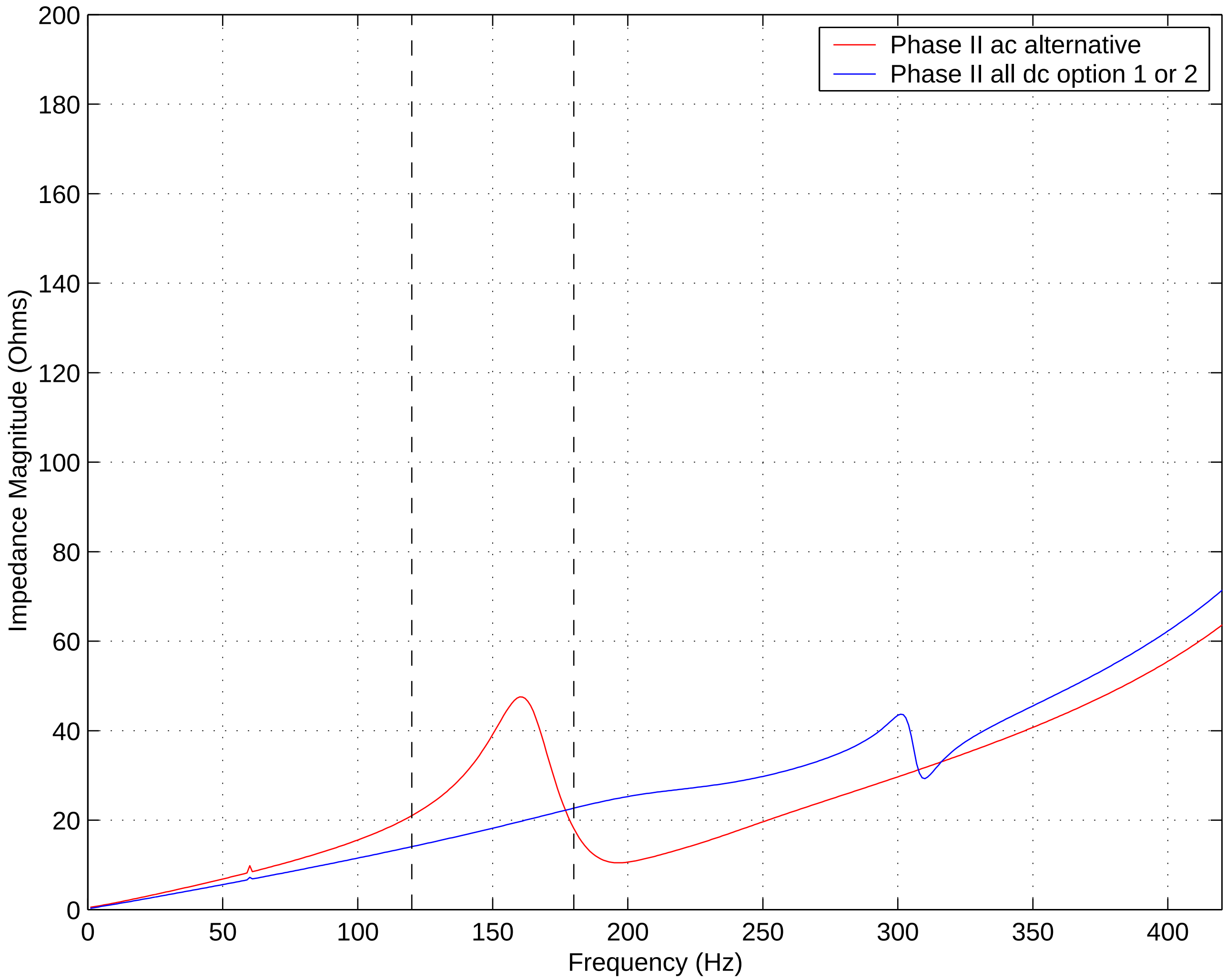


Figure D−30: Frequency Scan at Devon 345 kV − Cont 3

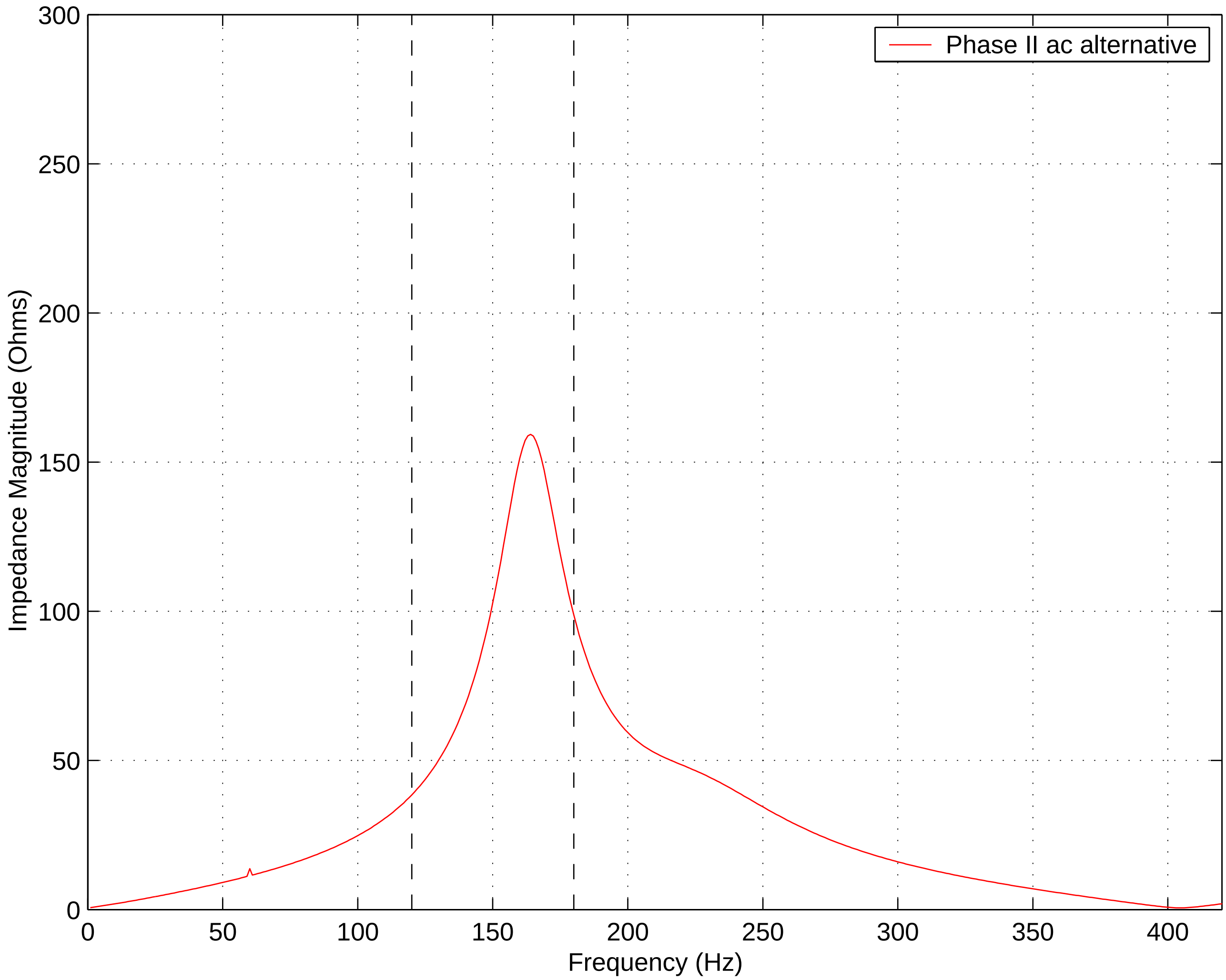
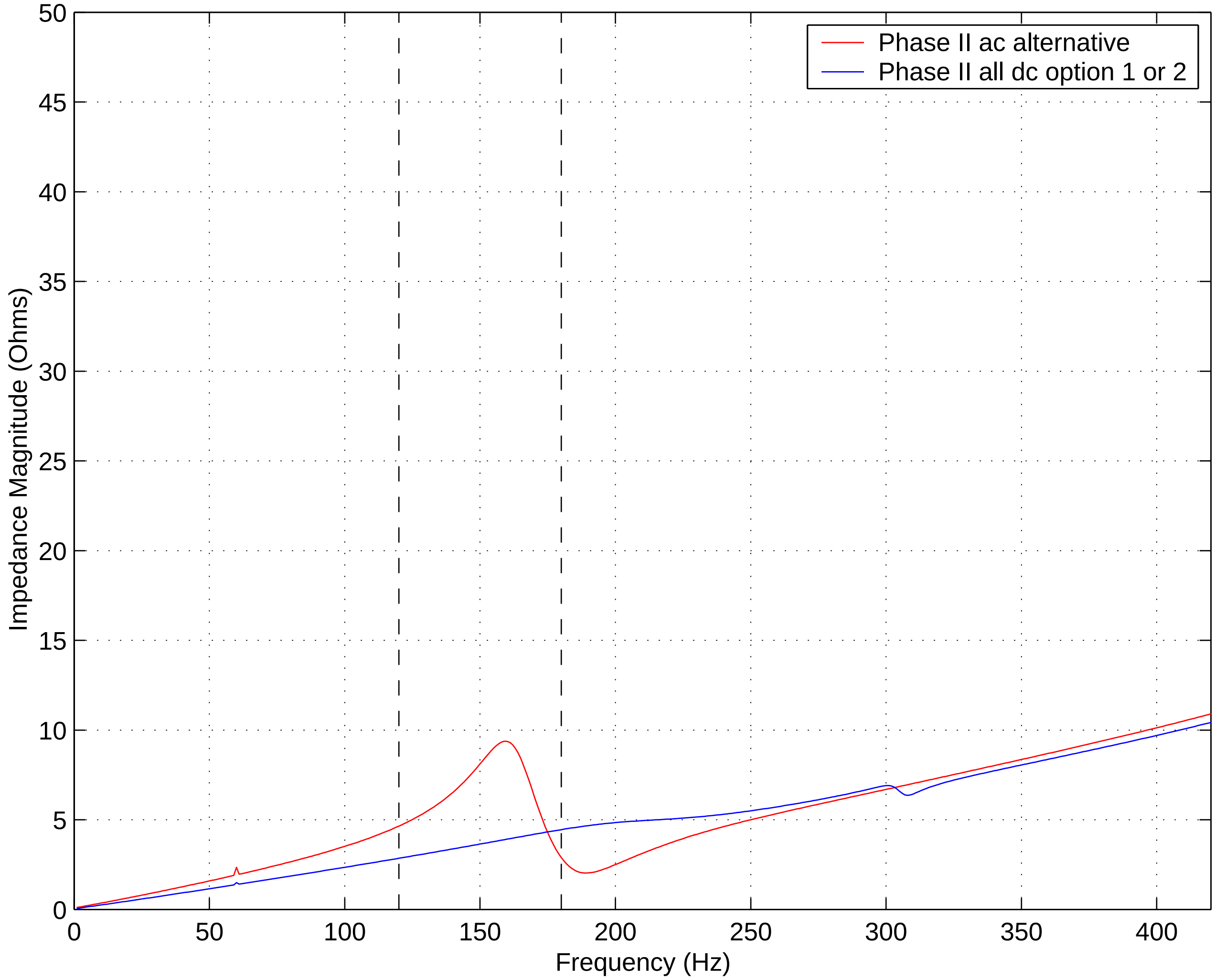


Figure D−31: Frequency Scan at Devon 115 kV − Cont 3



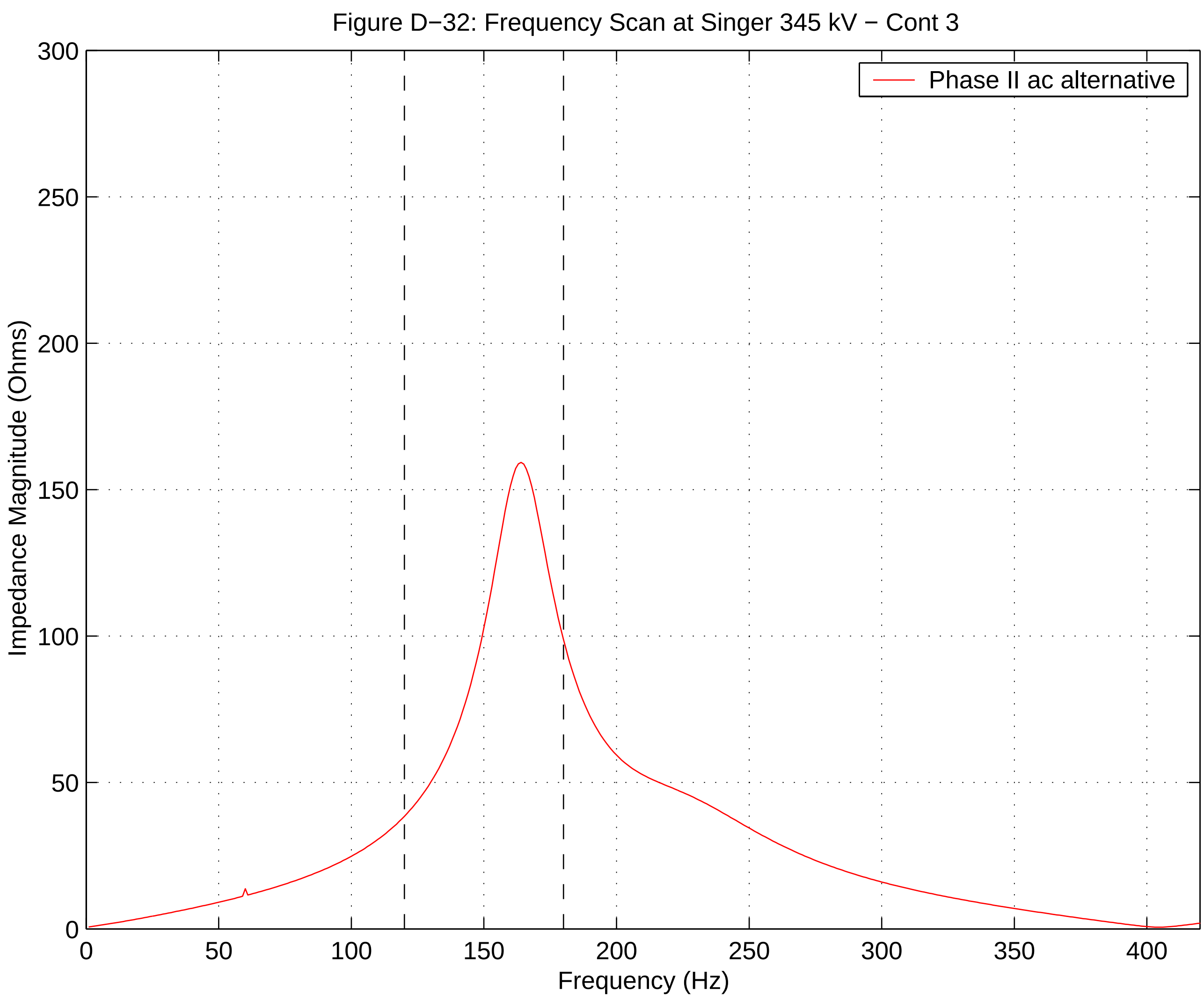


Figure D−32: Frequency Scan at Singer 345 kV − Cont 3
Phase II ac alternative
300
250
200
150
100
50
0
Impedance Magnitude (Ohms)
0
50
100
150
200
250
300
350
400
Frequency (Hz)

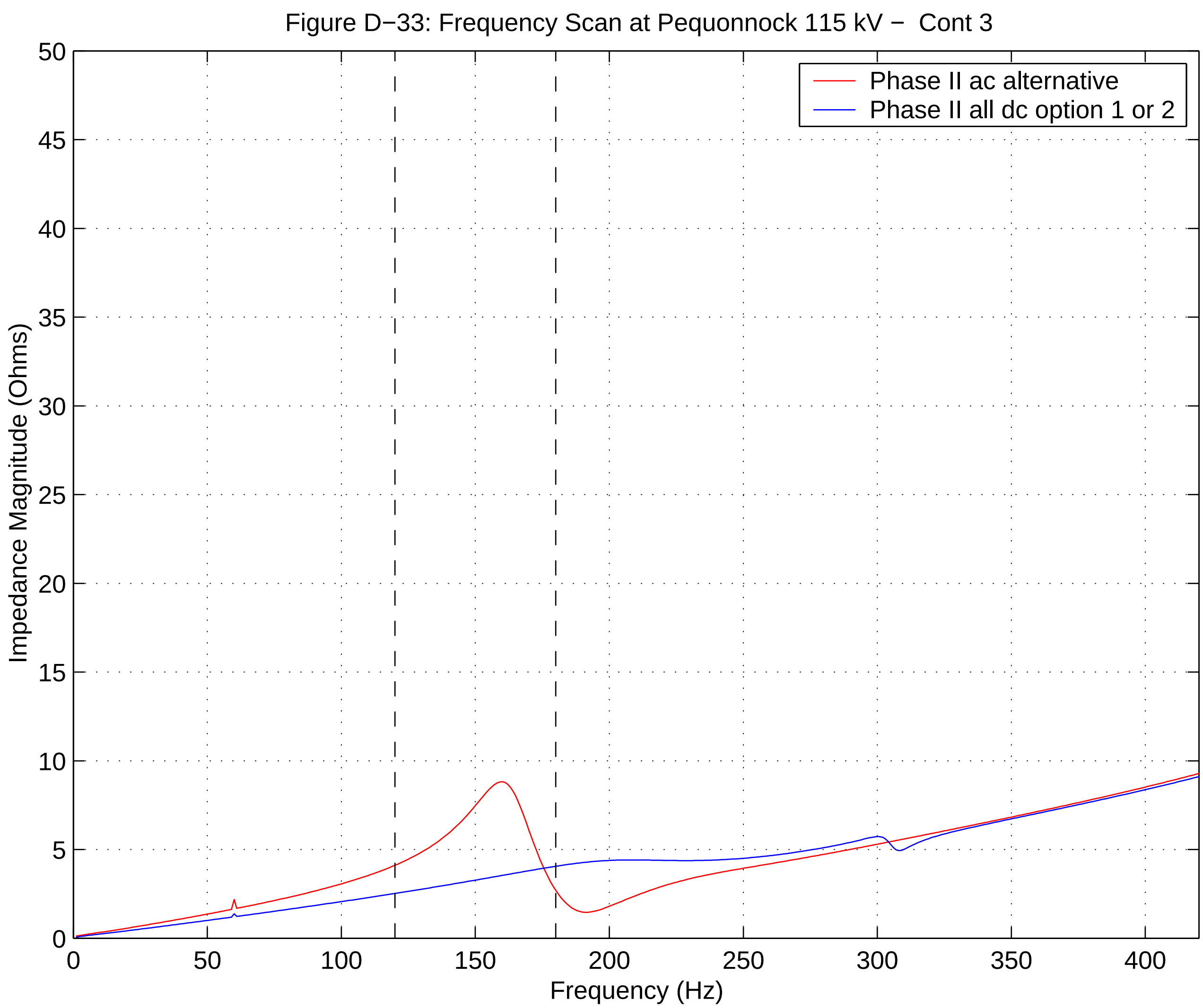


Figure D−33: Frequency Scan at Pequonnock 115 kV − Cont 3
Phase II ac alternative
Phase II all dc option 1 or 2
Impedance Magnitude (Ohms)
Frequency (Hz)
0
5
10
15
20
25
30
35
40
45
50
0
50
100
150
200
250
300
350
400

Figure D−34: Frequency Scan at Plumtree 345 kV − Cont 3

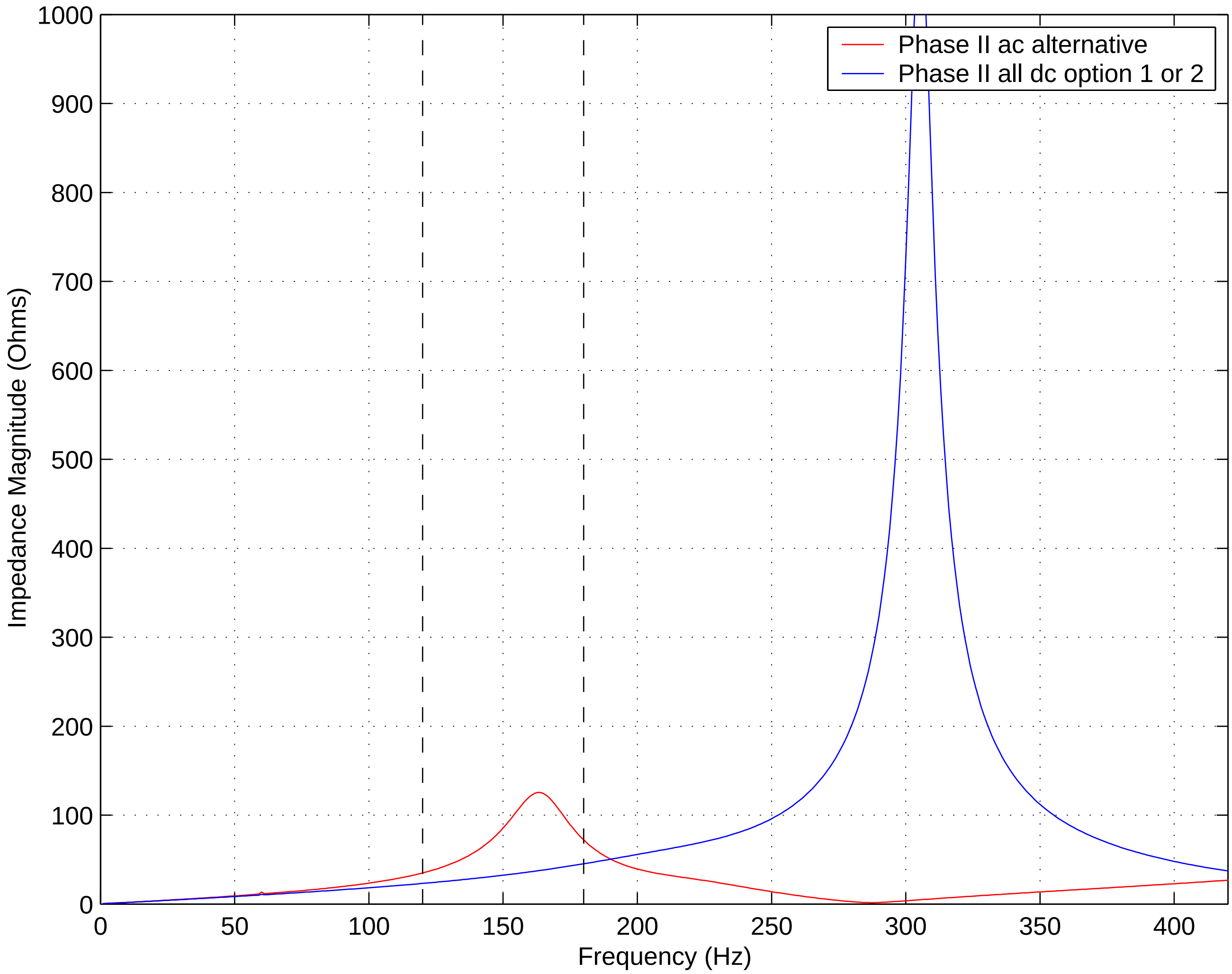


Figure D−35: Frequency Scan at Southington 345 kV − Cont 3

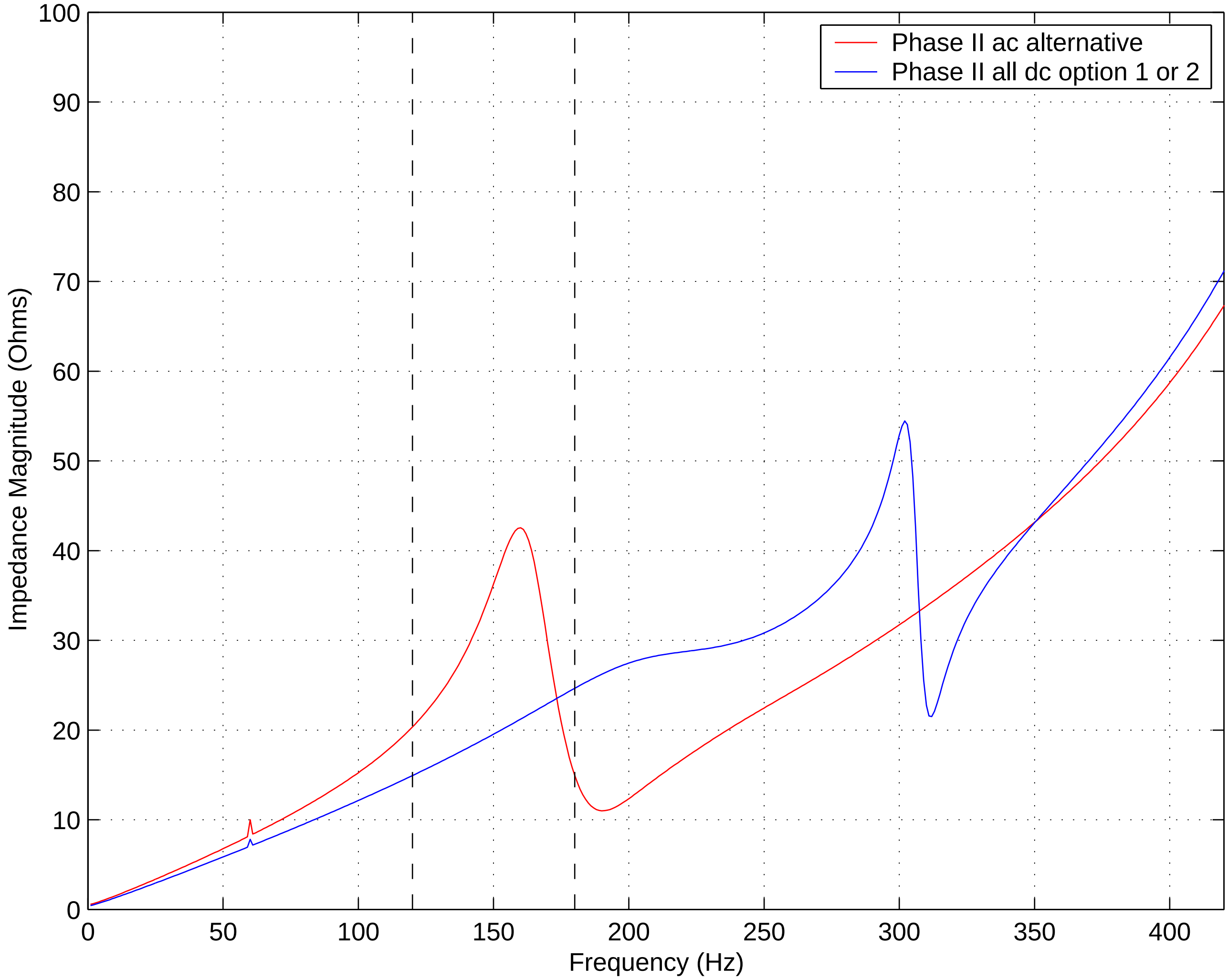


Figure D−36: Frequency Scan at Woodmont 115 kV − Cont 3

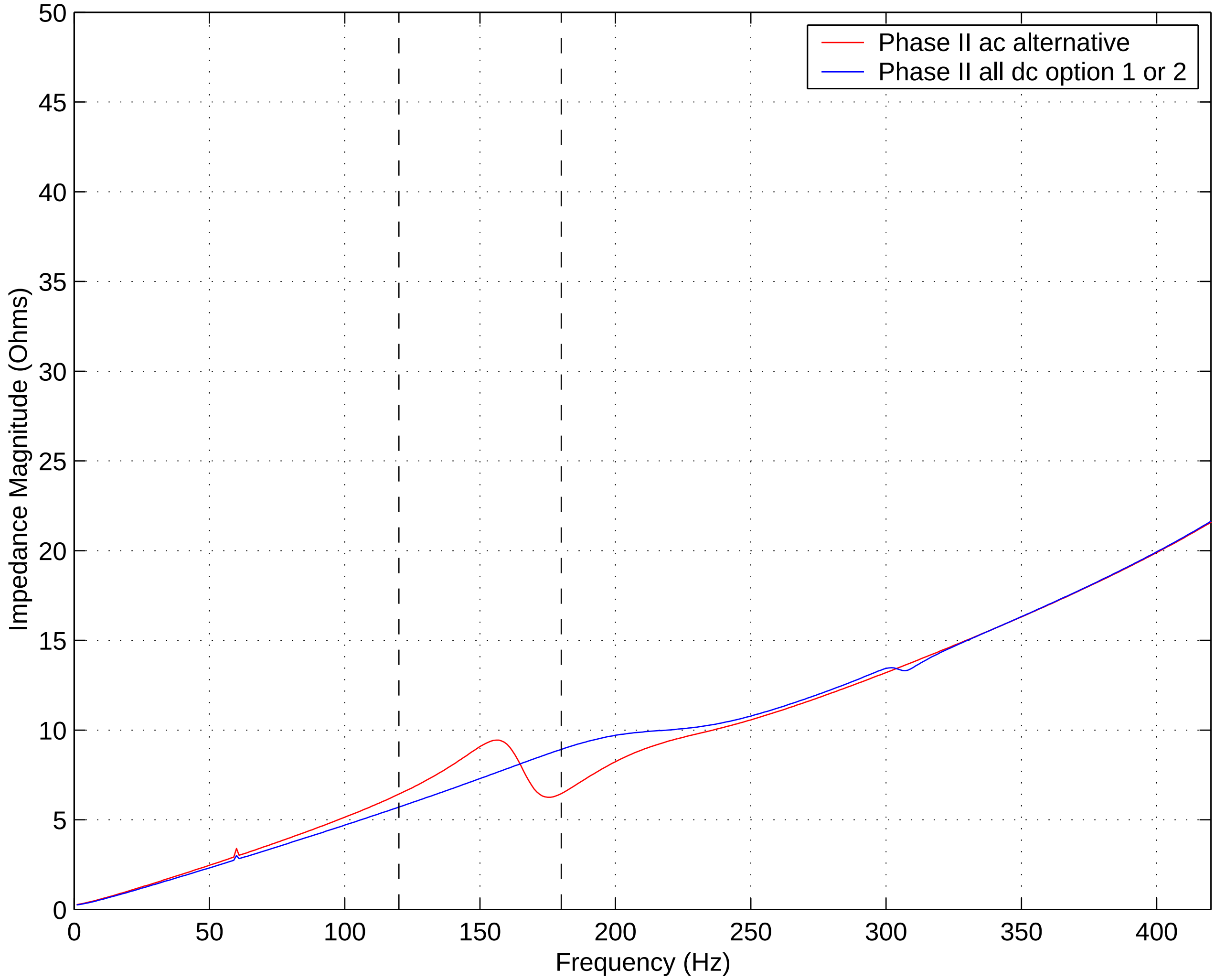
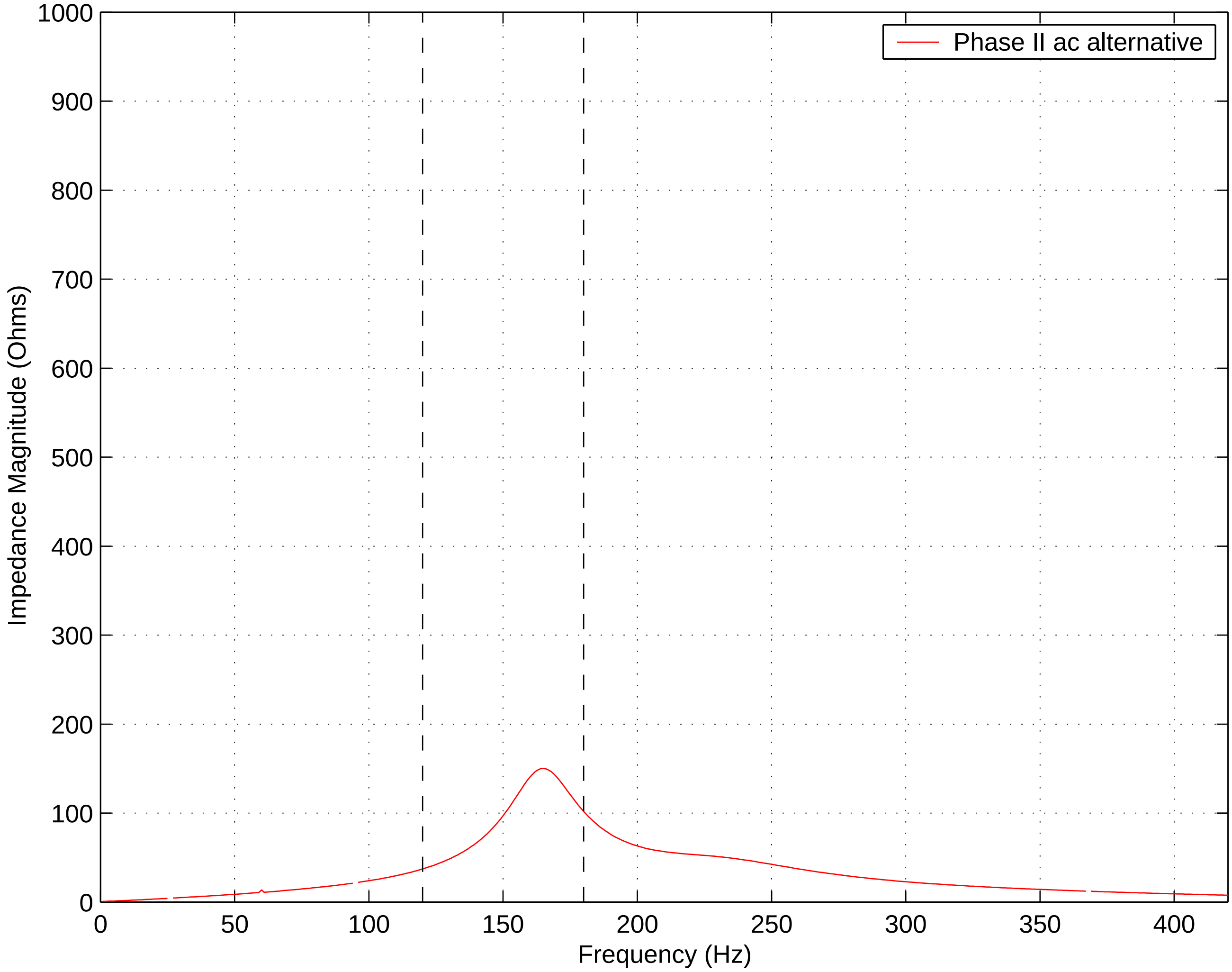


Figure D−37: Frequency Scan at Norwalk 345 kV − Cont 4



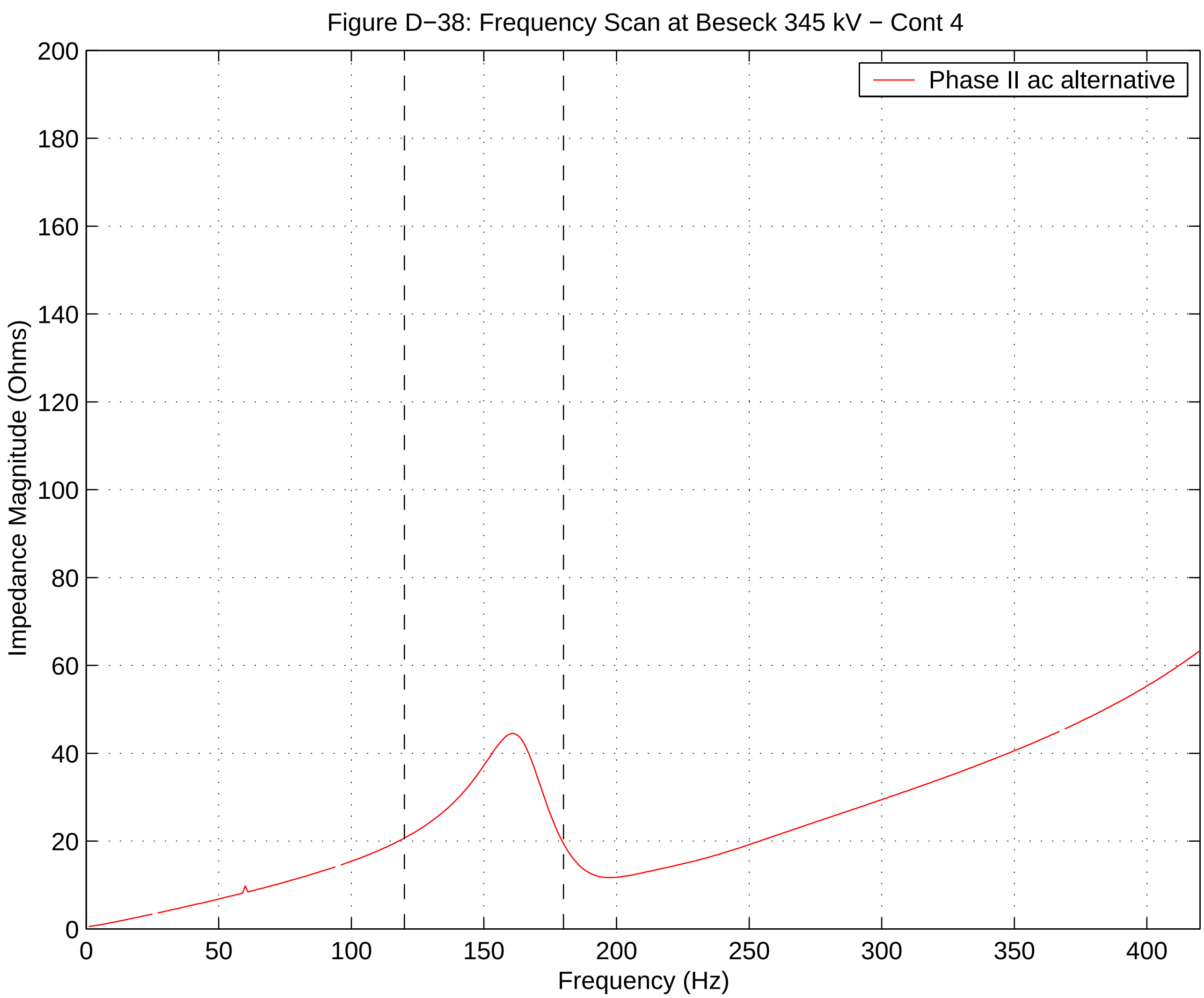


Figure D−38: Frequency Scan at Beseck 345 kV − Cont 4
Phase II ac alternative
Impedance Magnitude (Ohms)
Frequency (Hz)
0
20
40
60
80
100
120
140
160
180
200
0
50
100
150
200
250
300
350
400

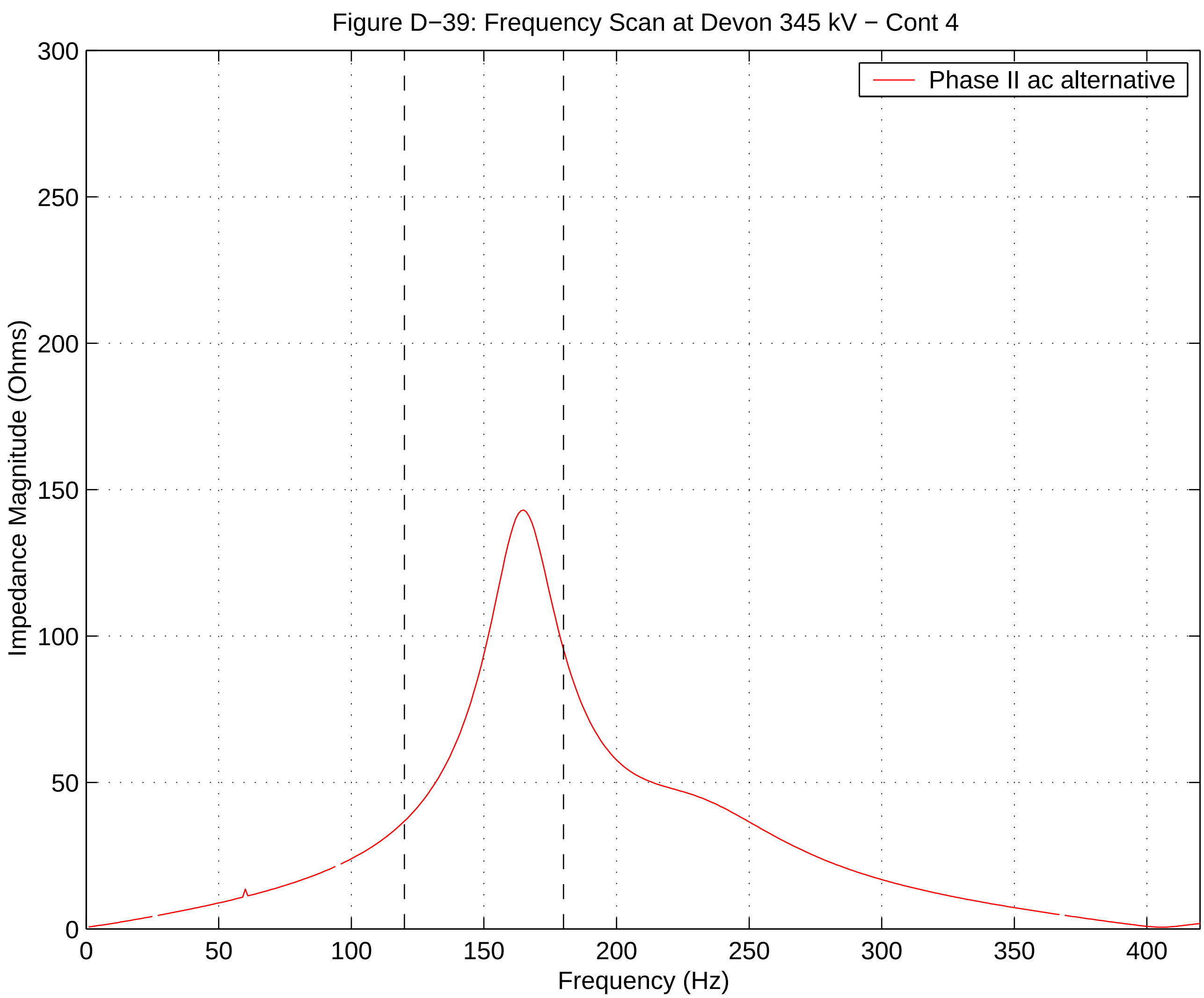


Figure D−39: Frequency Scan at Devon 345 kV − Cont 4
Phase II ac alternative
Impedance Magnitude (Ohms)
Frequency (Hz)
0
50
100
150
200
250
300
350
400

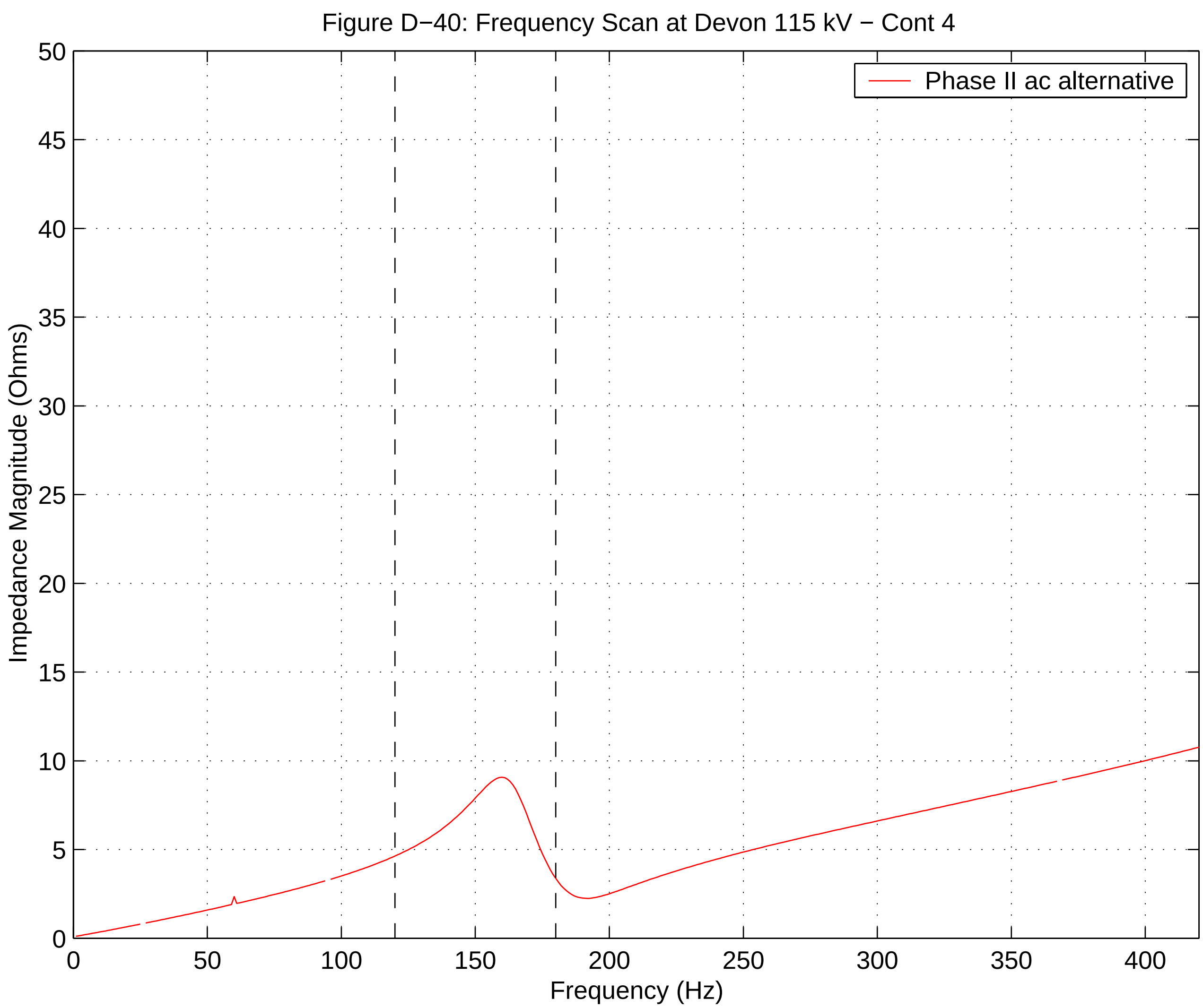
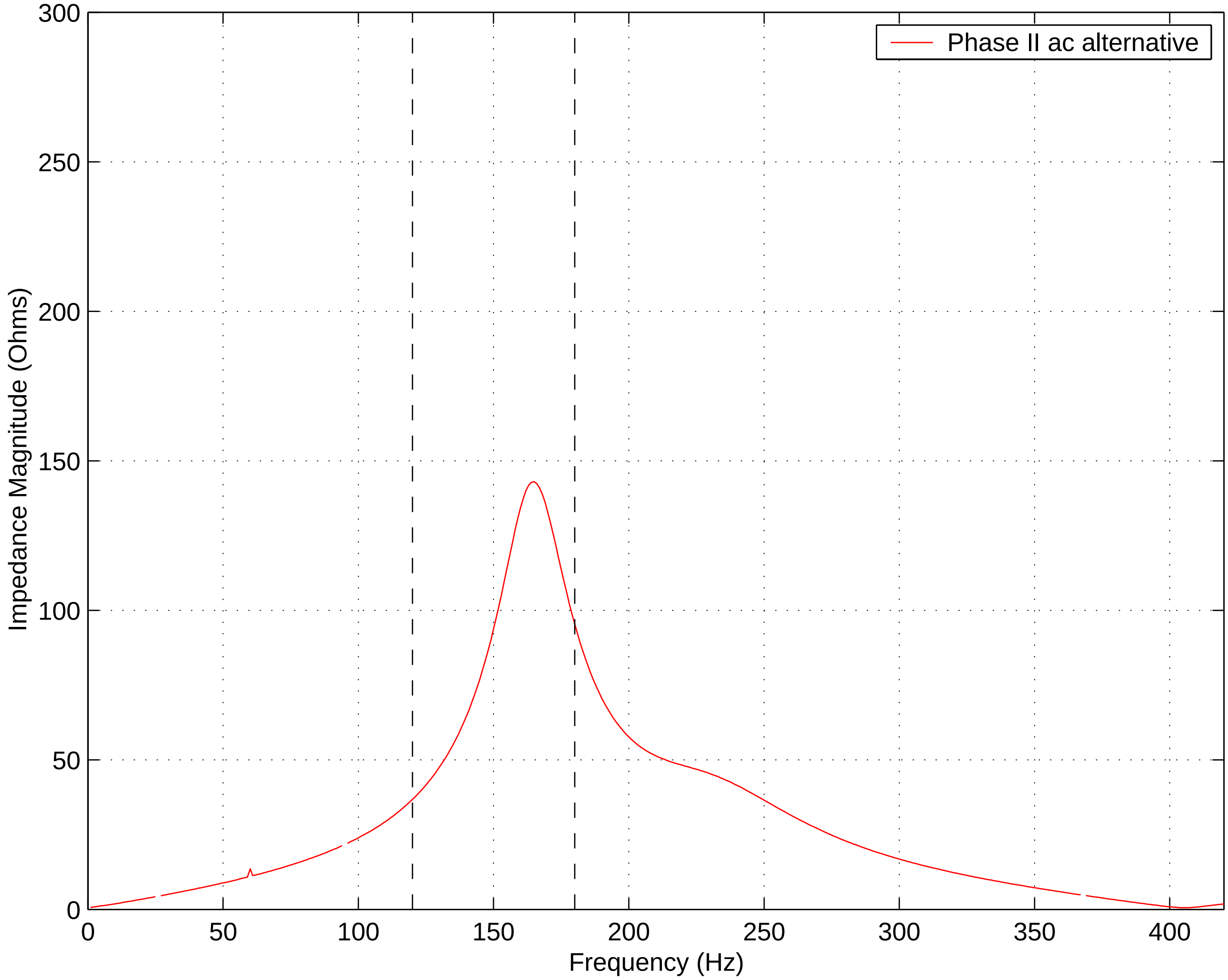


Figure D−40: Frequency Scan at Devon 115 kV − Cont 4
Phase II ac alternative
Impedance Magnitude (Ohms)
Frequency (Hz)
0
5
10
15
20
25
30
35
40
45
50
0
50
100
150
200
250
300
350
400

Figure D−41: Frequency Scan at Singer 345 kV − Cont 4



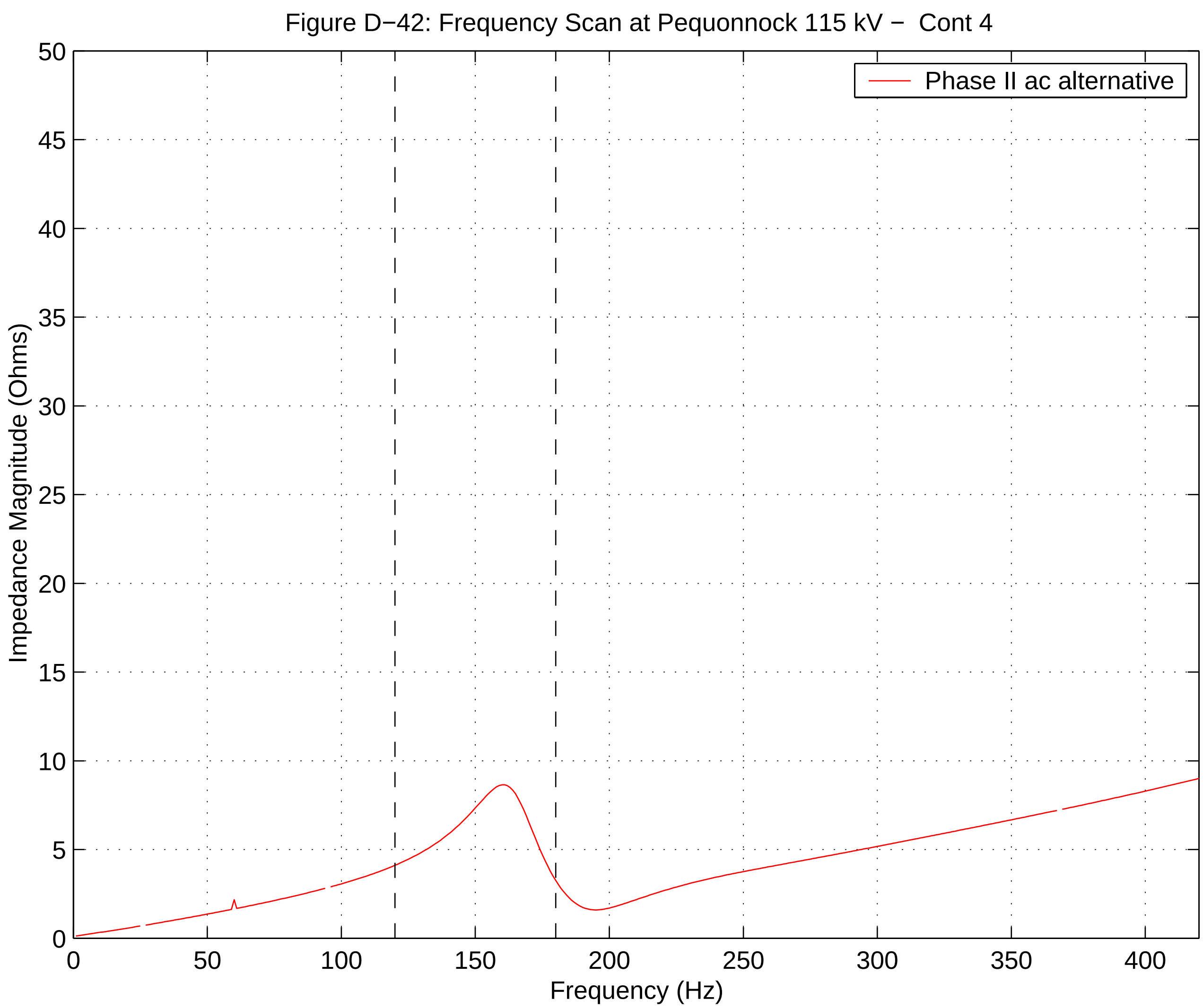


Figure D−42: Frequency Scan at Pequonnock 115 kV − Cont 4
Phase II ac alternative
Impedance Magnitude (Ohms)
Frequency (Hz)
0
5
10
15
20
25
30
35
40
45
50
0
50
100
150
200
250
300
350
400

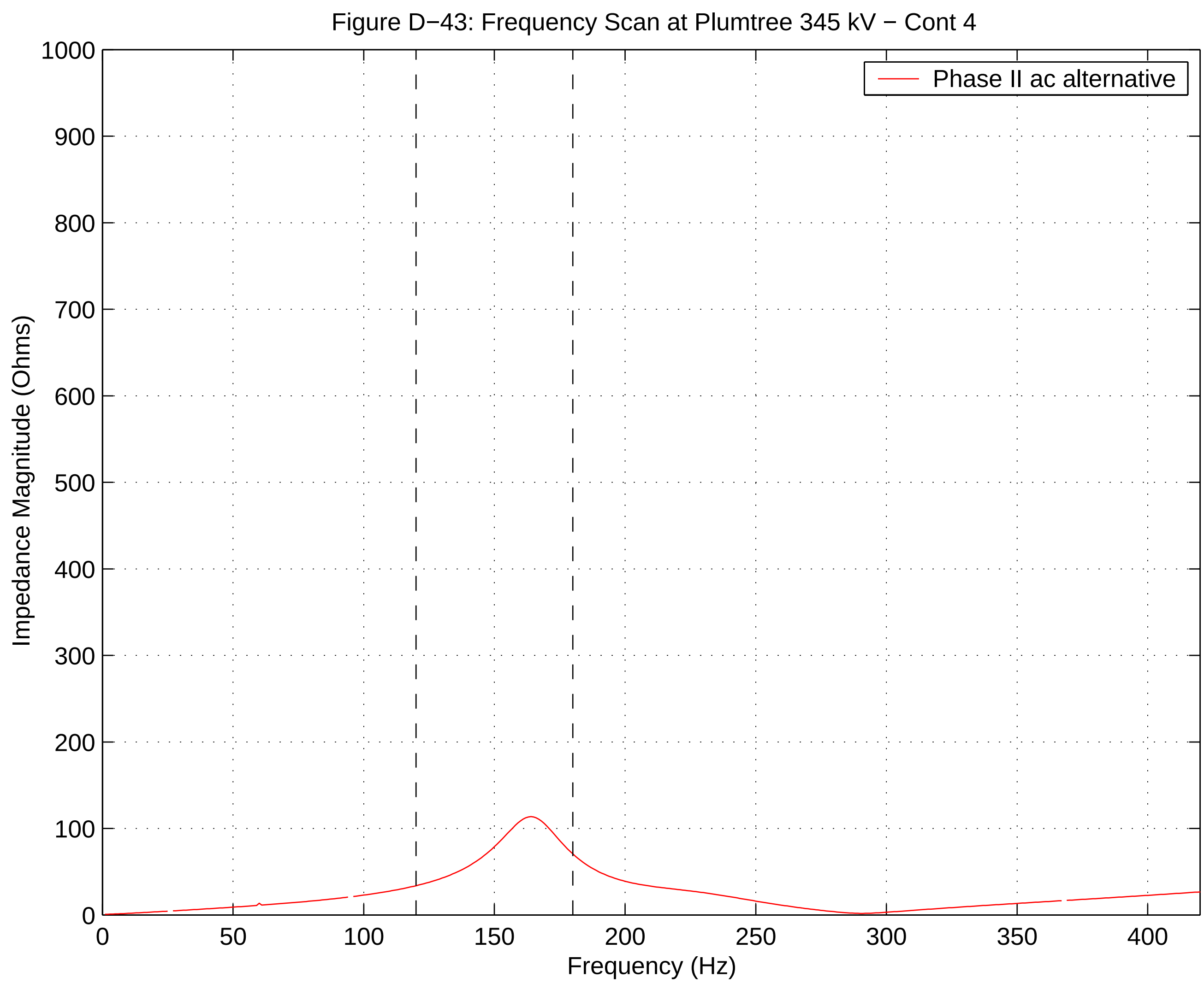


Figure D−43: Frequency Scan at Plumtree 345 kV − Cont 4
Phase II ac alternative
Impedance Magnitude (Ohms)
Frequency (Hz)
0
100
200
300
400
500
600
700
800
900
1000
0
50
100
150
200
250
300
350
400

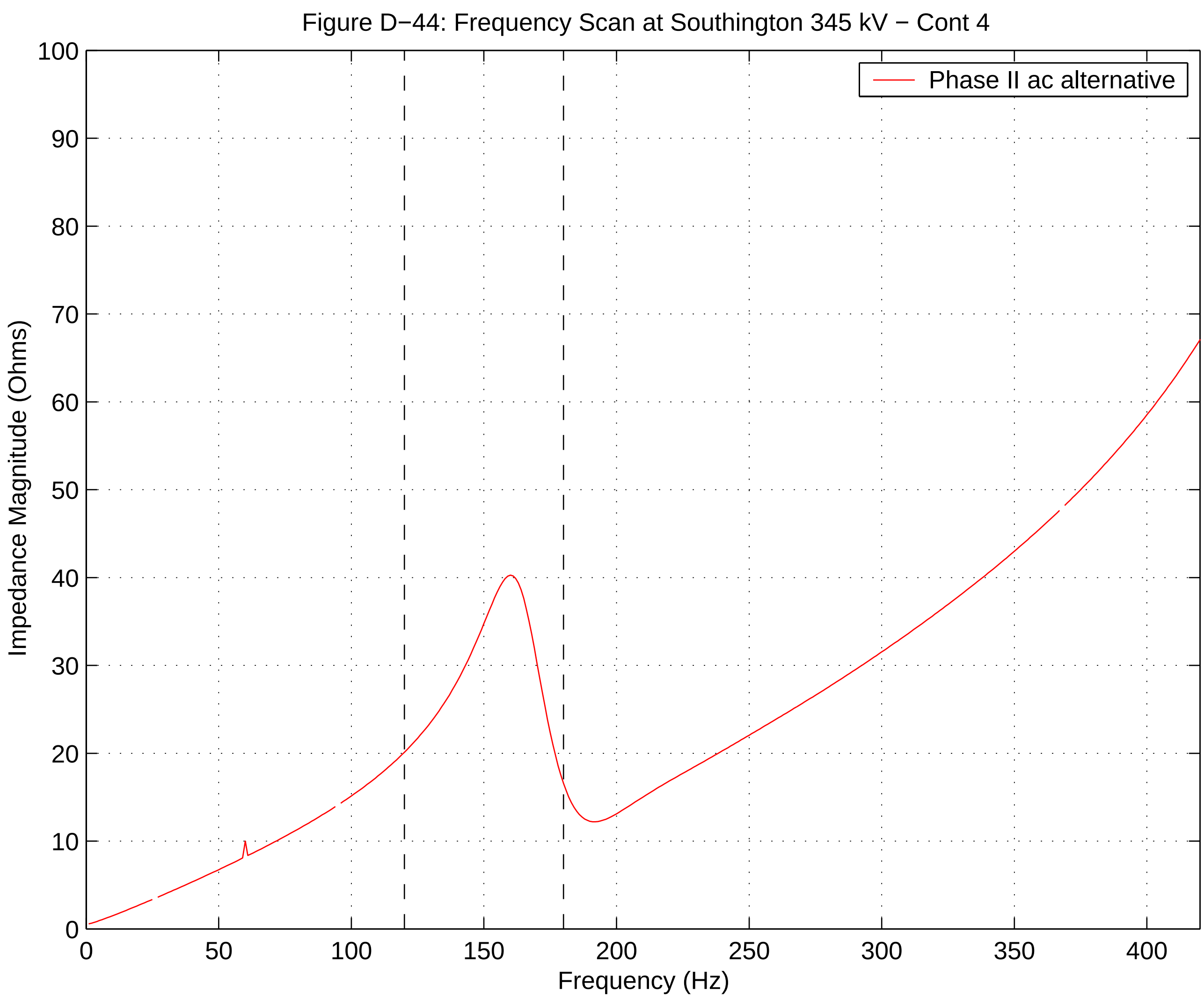
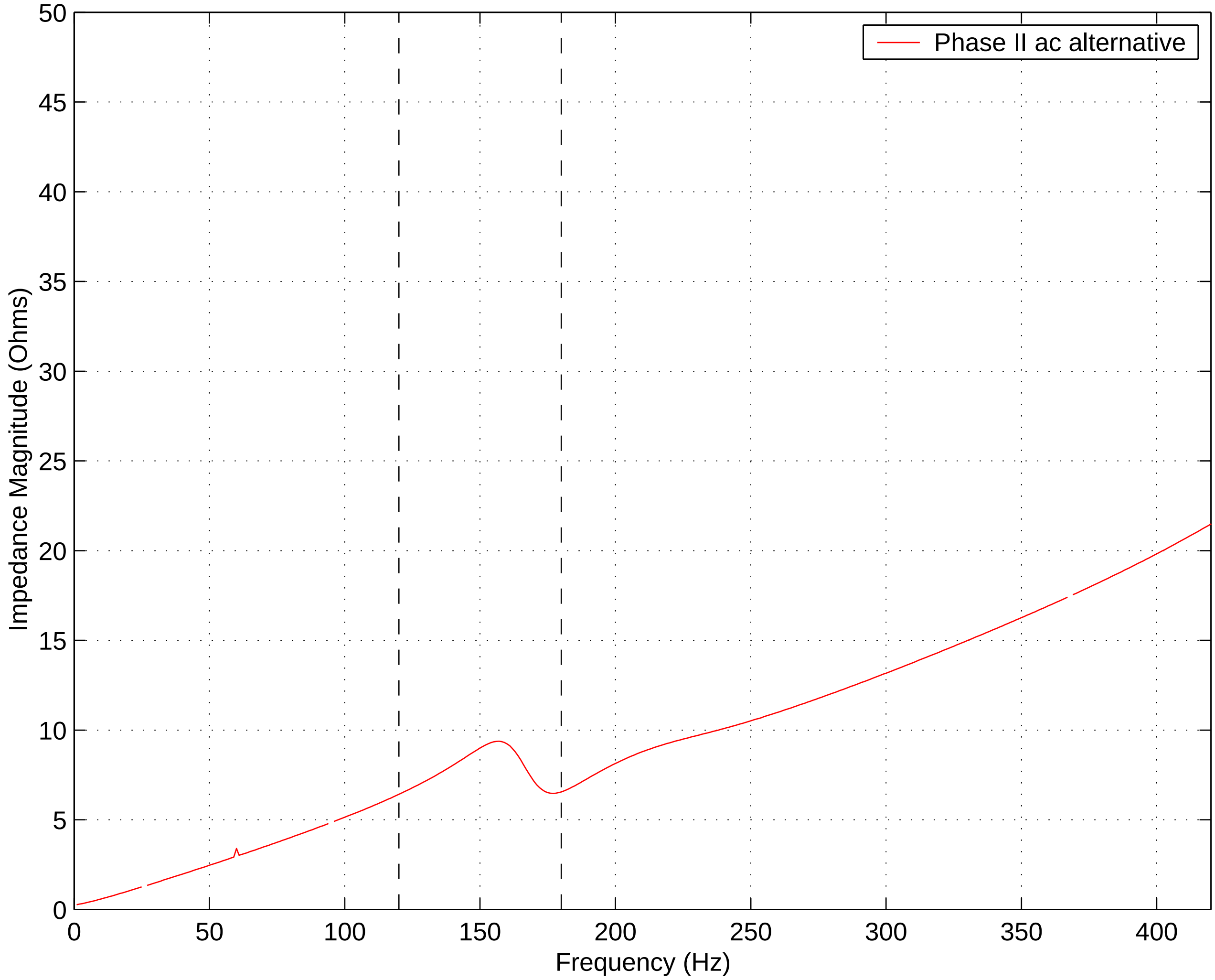


Figure D−44: Frequency Scan at Southington 345 kV − Cont 4
Phase II ac alternative
Impedance Magnitude (Ohms)
Frequency (Hz)
0
10
20
30
40
50
60
70
80
90
100
0
50
100
150
200
250
300
350
400

Figure D−45: Frequency Scan at Woodmont 115 kV − Cont 4



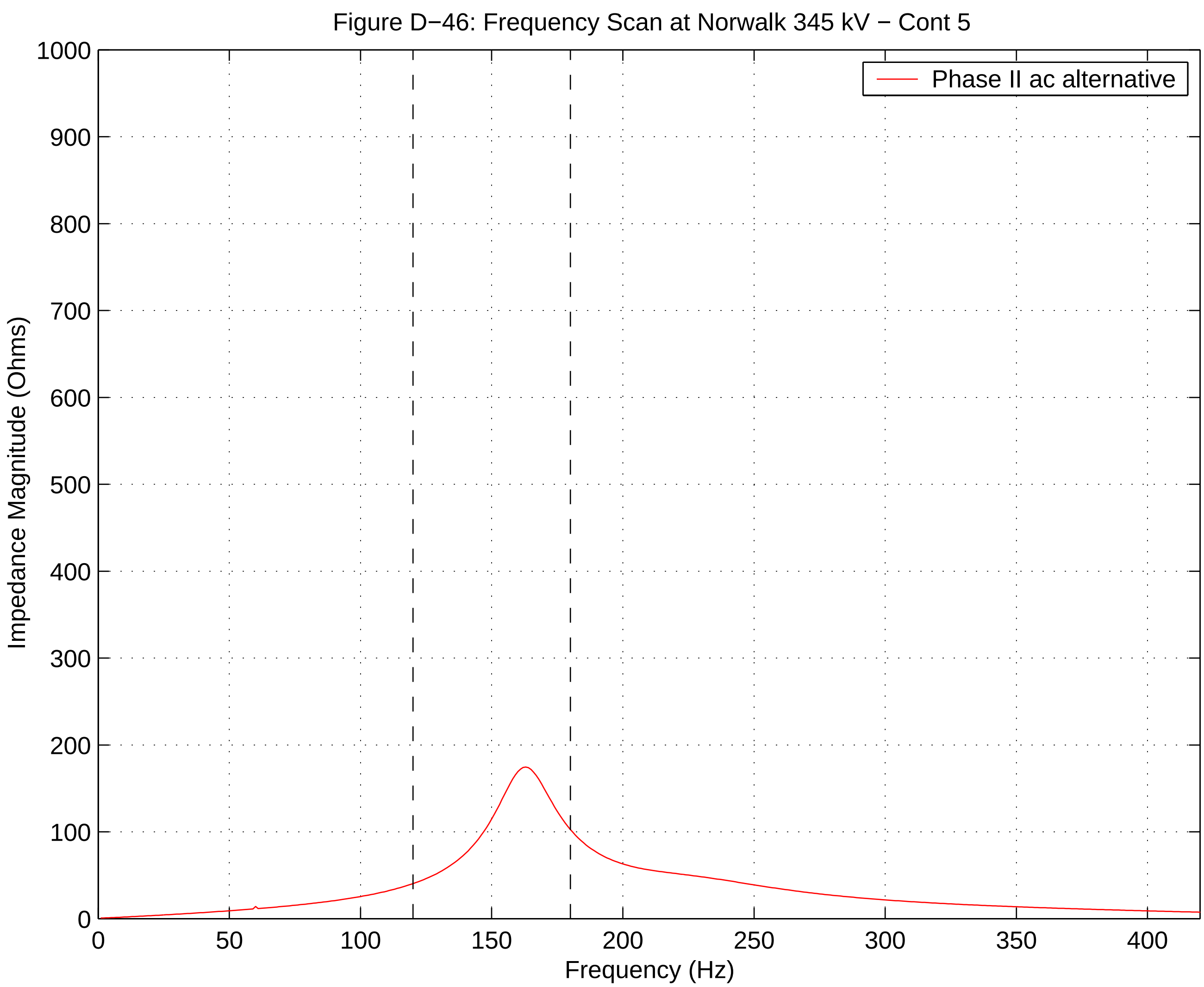


Figure D−46: Frequency Scan at Norwalk 345 kV − Cont 5
Phase II ac alternative
Impedance Magnitude (Ohms)
Frequency (Hz)
0
100
200
300
400
500
600
700
800
900
1000
0
50
100
150
200
250
300
350
400

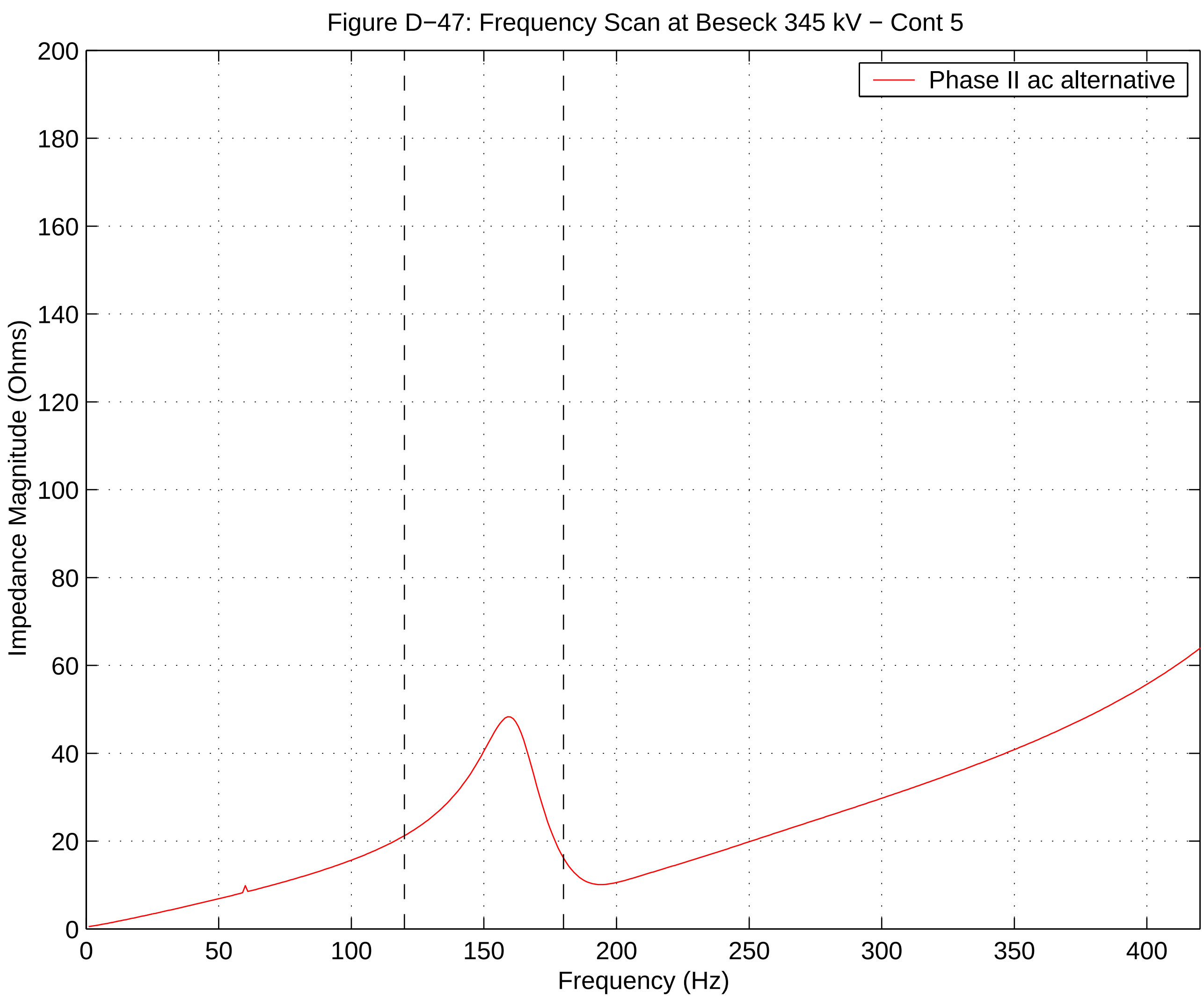


Figure D−47: Frequency Scan at Beseck 345 kV − Cont 5
Phase II ac alternative
Impedance Magnitude (Ohms)
Frequency (Hz)
0
20
40
60
80
100
120
140
160
180
200
0
50
100
150
200
250
300
350
400

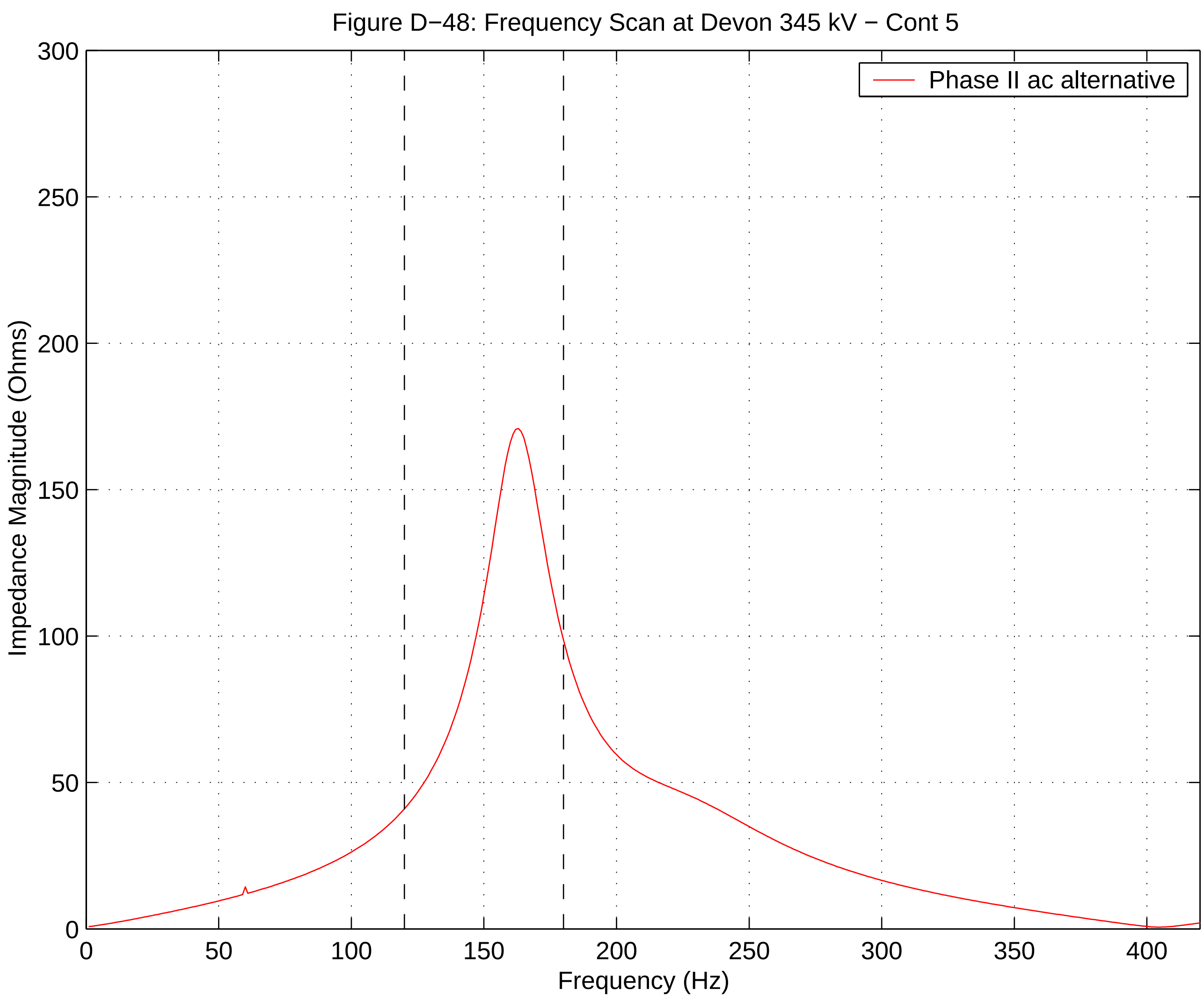


Figure D−48: Frequency Scan at Devon 345 kV − Cont 5
Phase II ac alternative
Impedance Magnitude (Ohms)
Frequency (Hz)
0
50
100
150
200
250
300
350
400

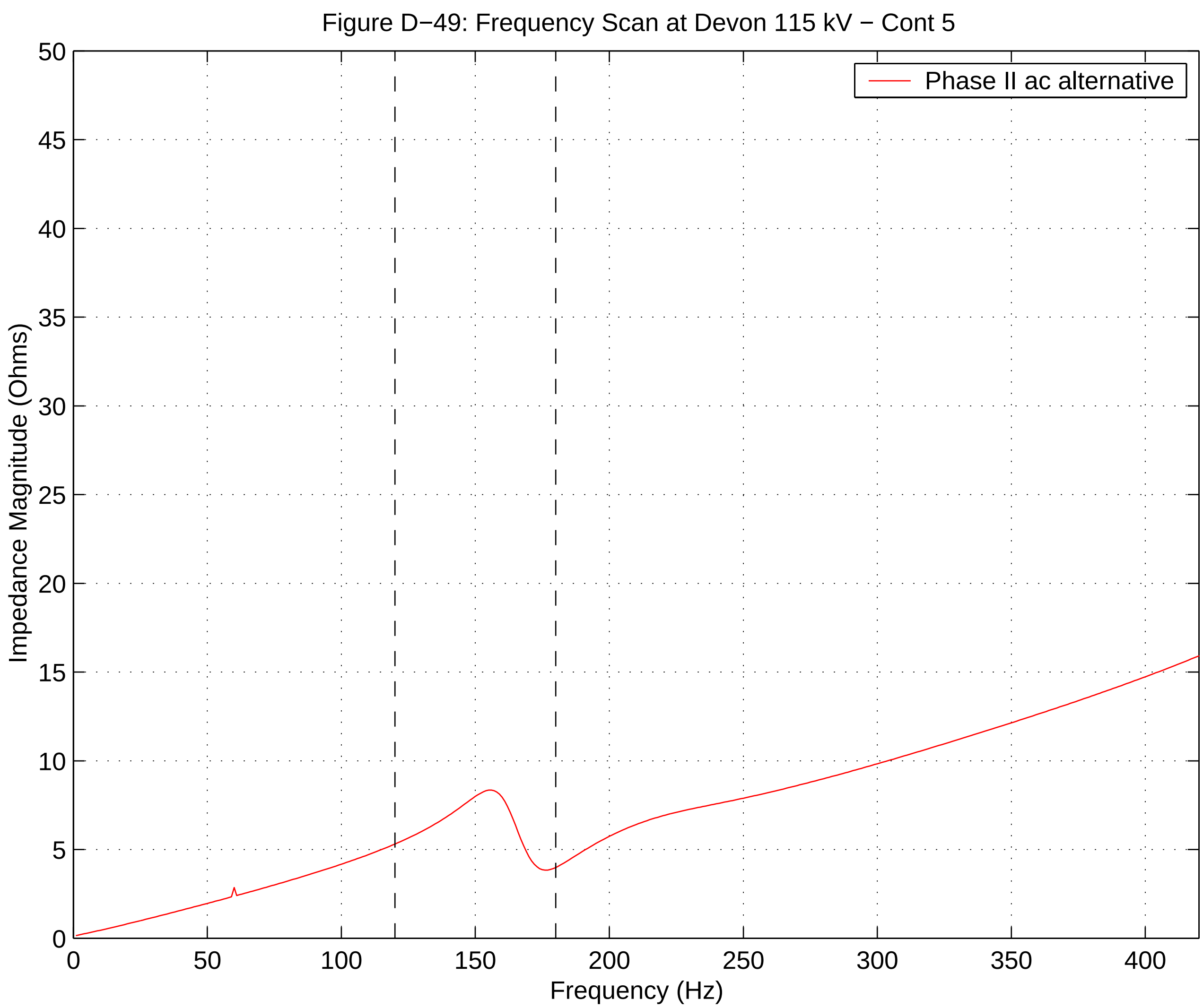


Figure D−49: Frequency Scan at Devon 115 kV − Cont 5
Phase II ac alternative
Impedance Magnitude (Ohms)
Frequency (Hz)
0
5
10
15
20
25
30
35
40
45
50
0
50
100
150
200
250
300
350
400

Figure D−50: Frequency Scan at Singer 345 kV − Cont 5

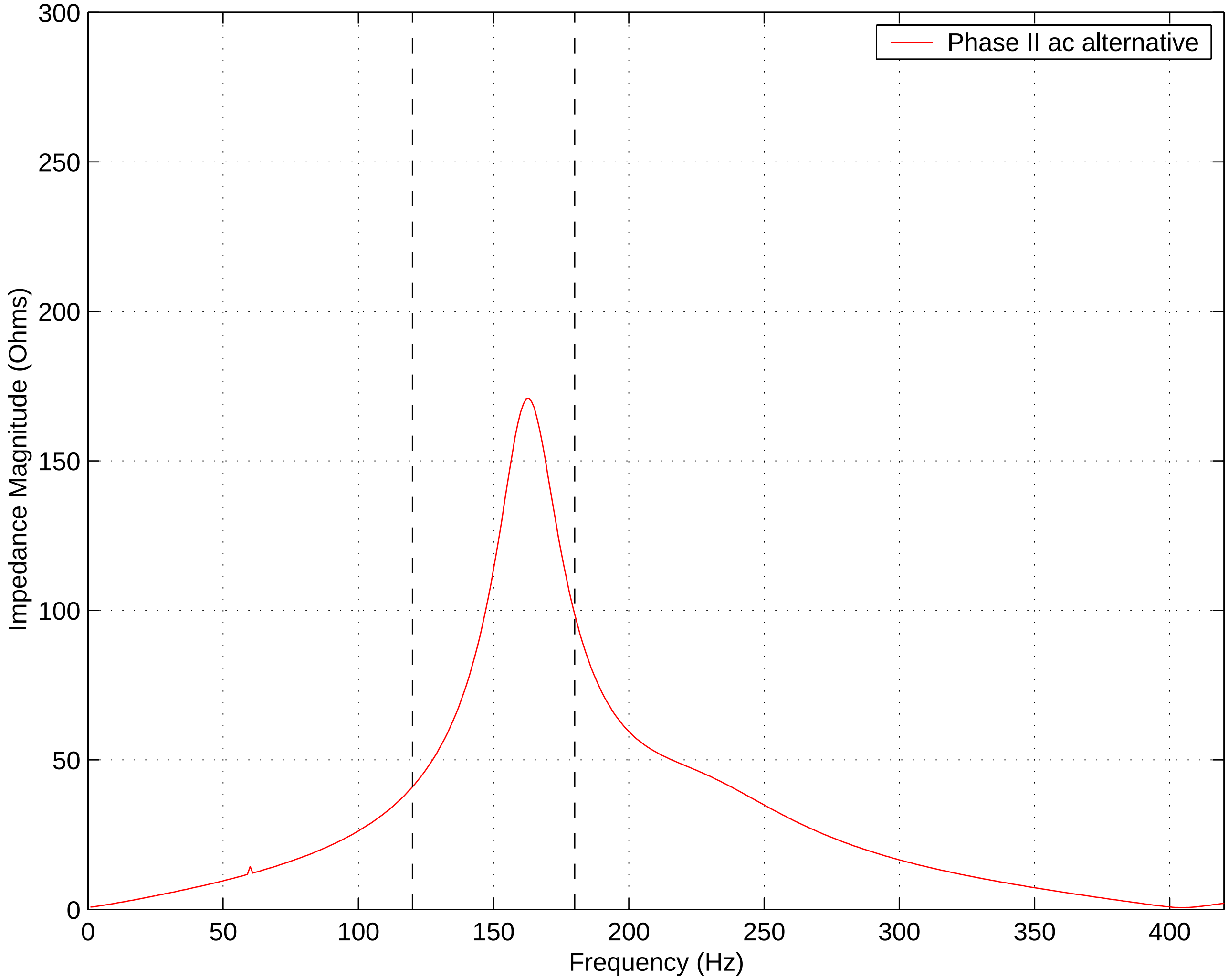
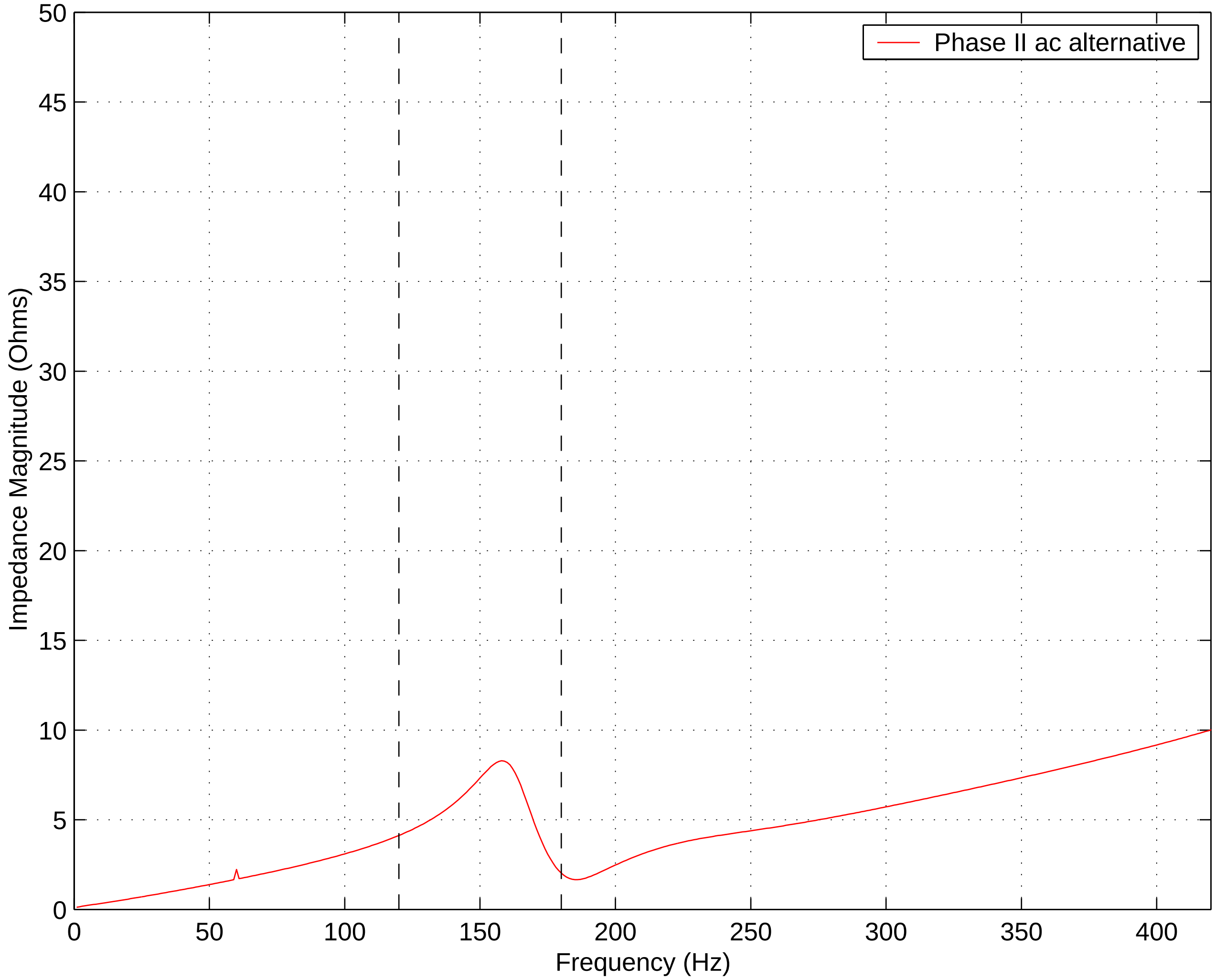


Figure D−51: Frequency Scan at Pequonnock 115 kV − Cont 5



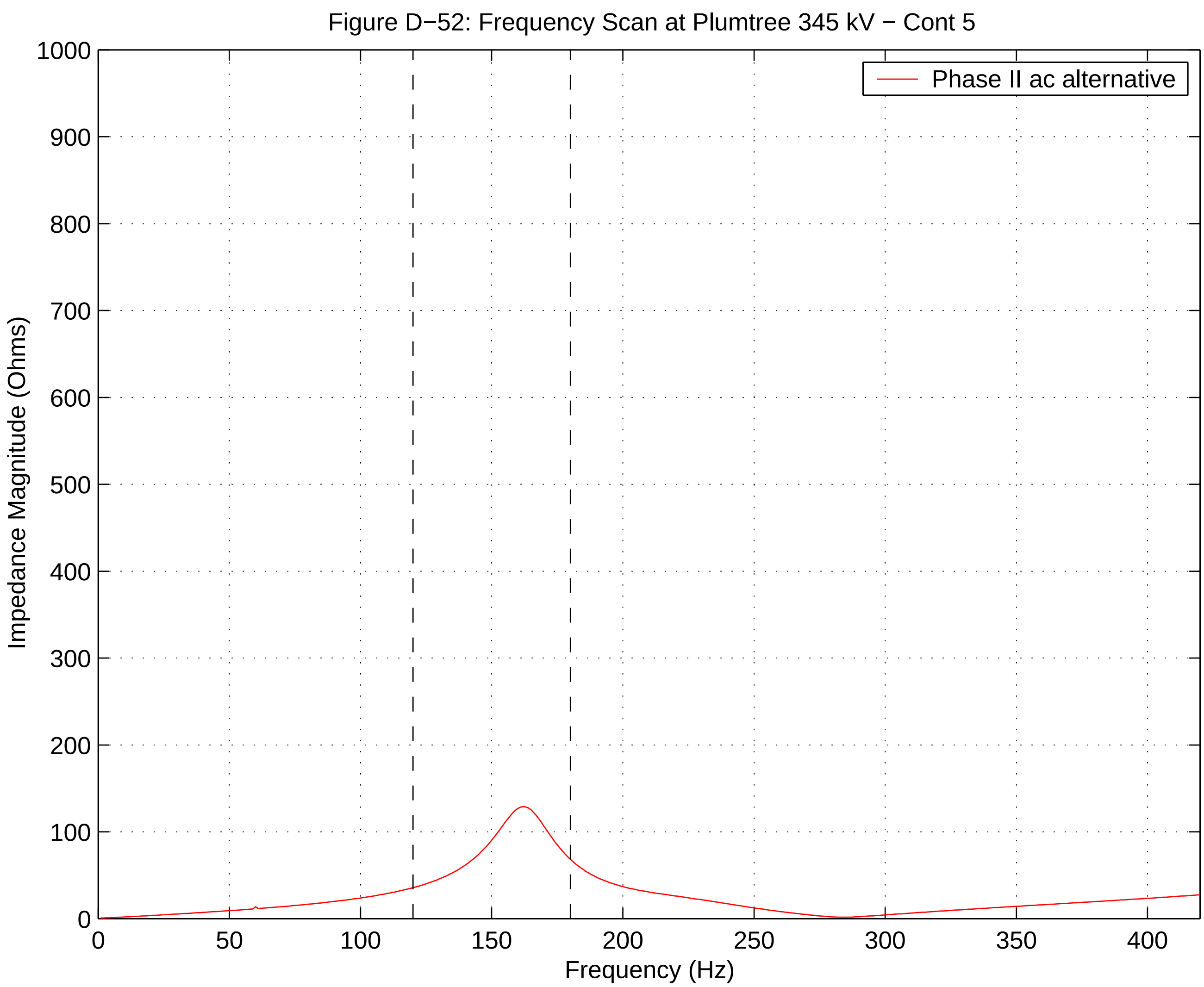
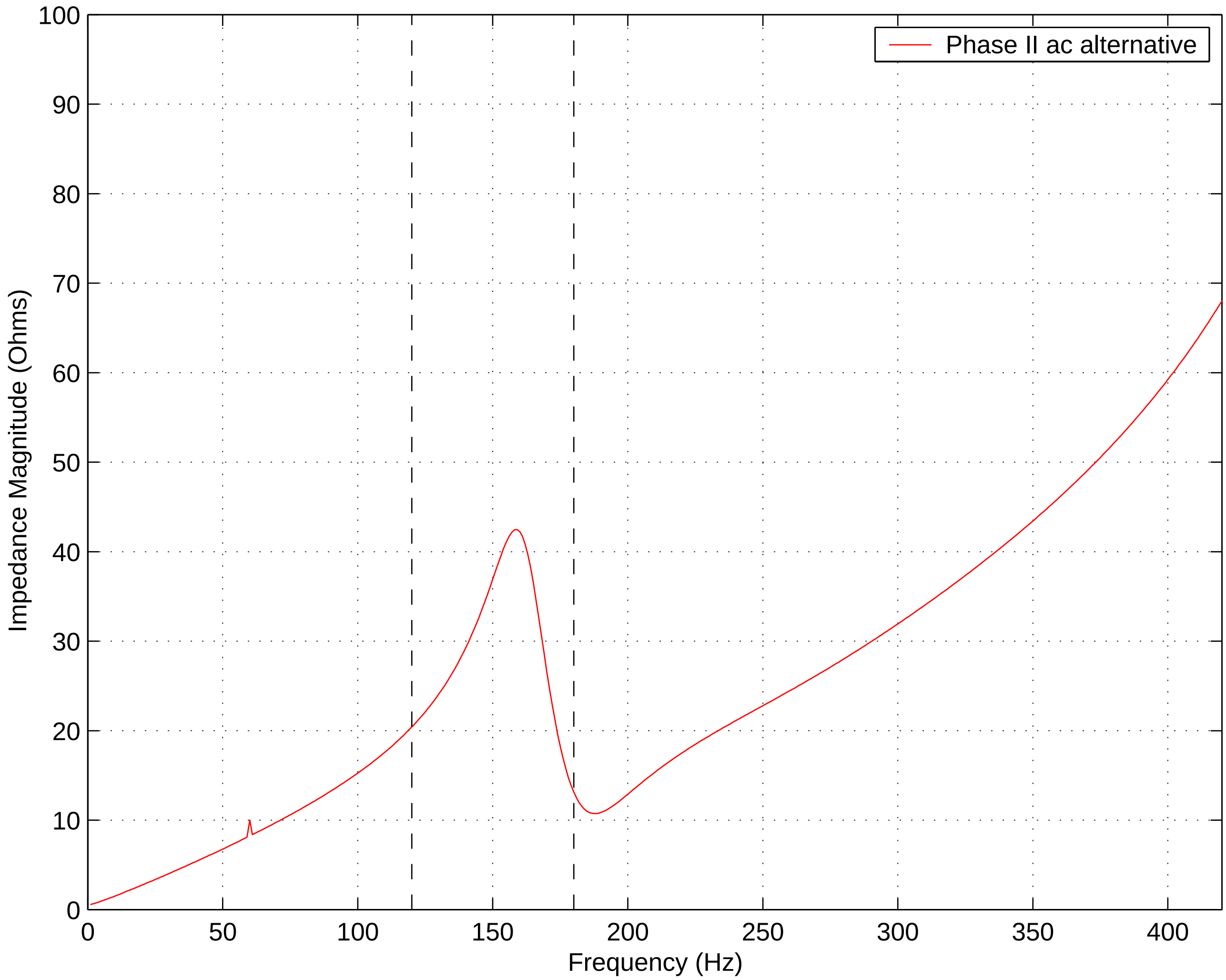


Figure D−52: Frequency Scan at Plumtree 345 kV − Cont 5
Phase II ac alternative
Impedance Magnitude (Ohms)
Frequency (Hz)
0
100
200
300
400
500
600
700
800
900
1000
0
50
100
150
200
250
300
350
400

Figure D−53: Frequency Scan at Southington 345 kV − Cont 5



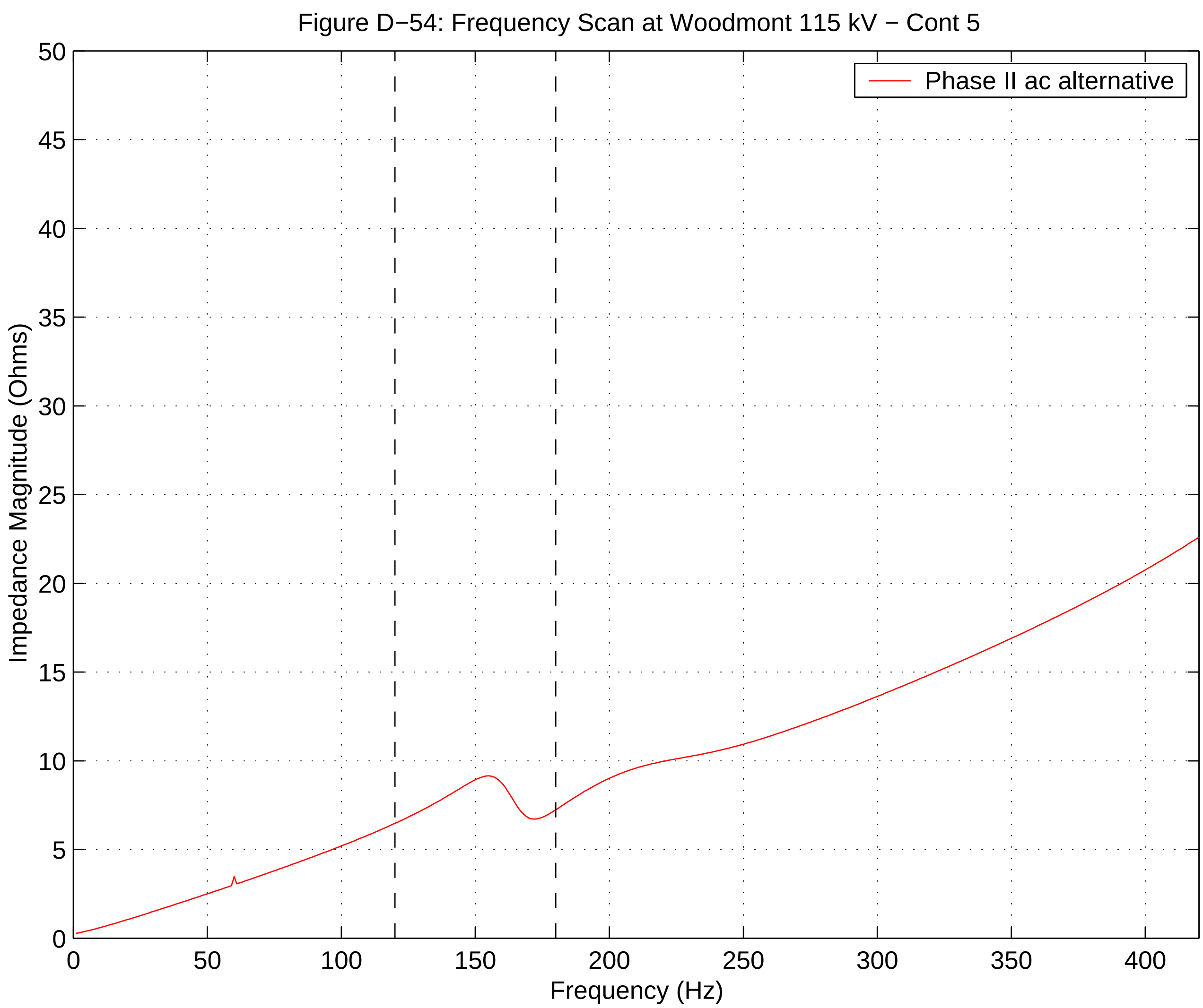


Figure D−54: Frequency Scan at Woodmont 115 kV − Cont 5
Phase II ac alternative
Impedance Magnitude (Ohms)
Frequency (Hz)
0
5
10
15
20
25
30
35
40
45
50
0
50
100
150
200
250
300
350
400

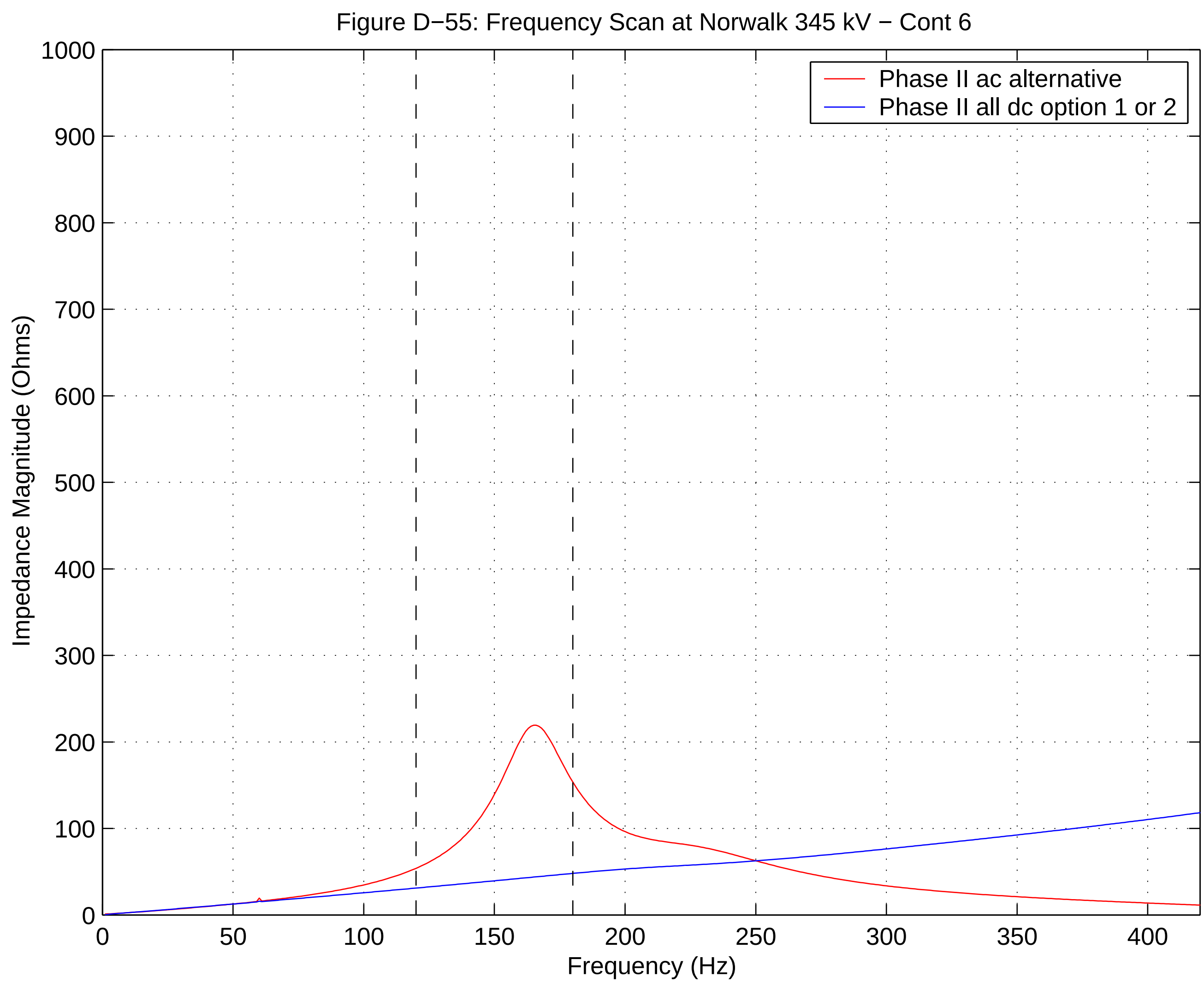


Figure D−55: Frequency Scan at Norwalk 345 kV − Cont 6
Phase II ac alternative
Phase II all dc option 1 or 2
Impedance Magnitude (Ohms)
Frequency (Hz)
0
100
200
300
400
500
600
700
800
900
1000
0
50
100
150
200
250
300
350
400

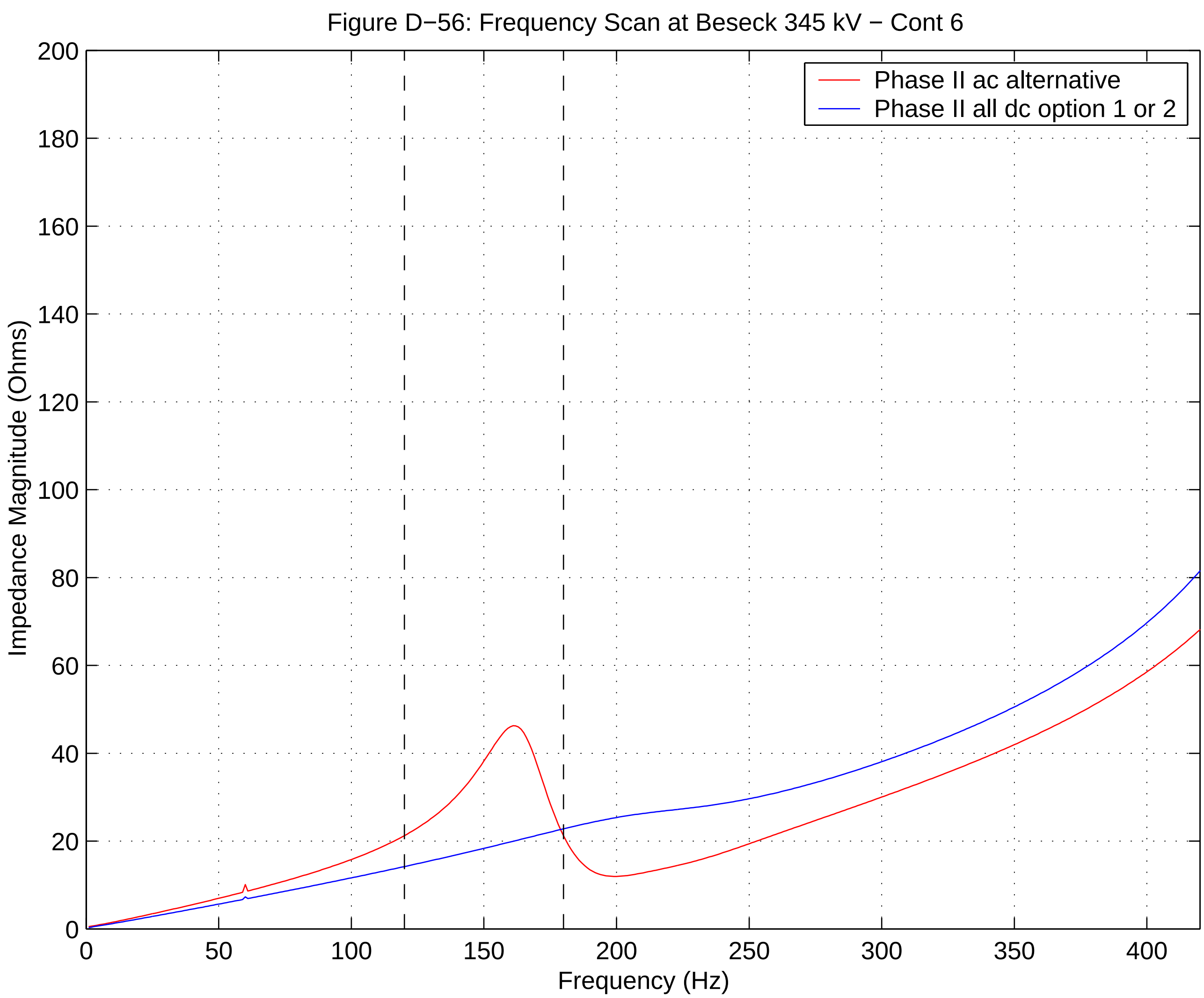


Figure D−56: Frequency Scan at Beseck 345 kV − Cont 6
Phase II ac alternative
Phase II all dc option 1 or 2
Impedance Magnitude (Ohms)
Frequency (Hz)
0
20
40
60
80
100
120
140
160
180
200
0
50
100
150
200
250
300
350
400

Figure D−57: Frequency Scan at Devon 345 kV − Cont 6

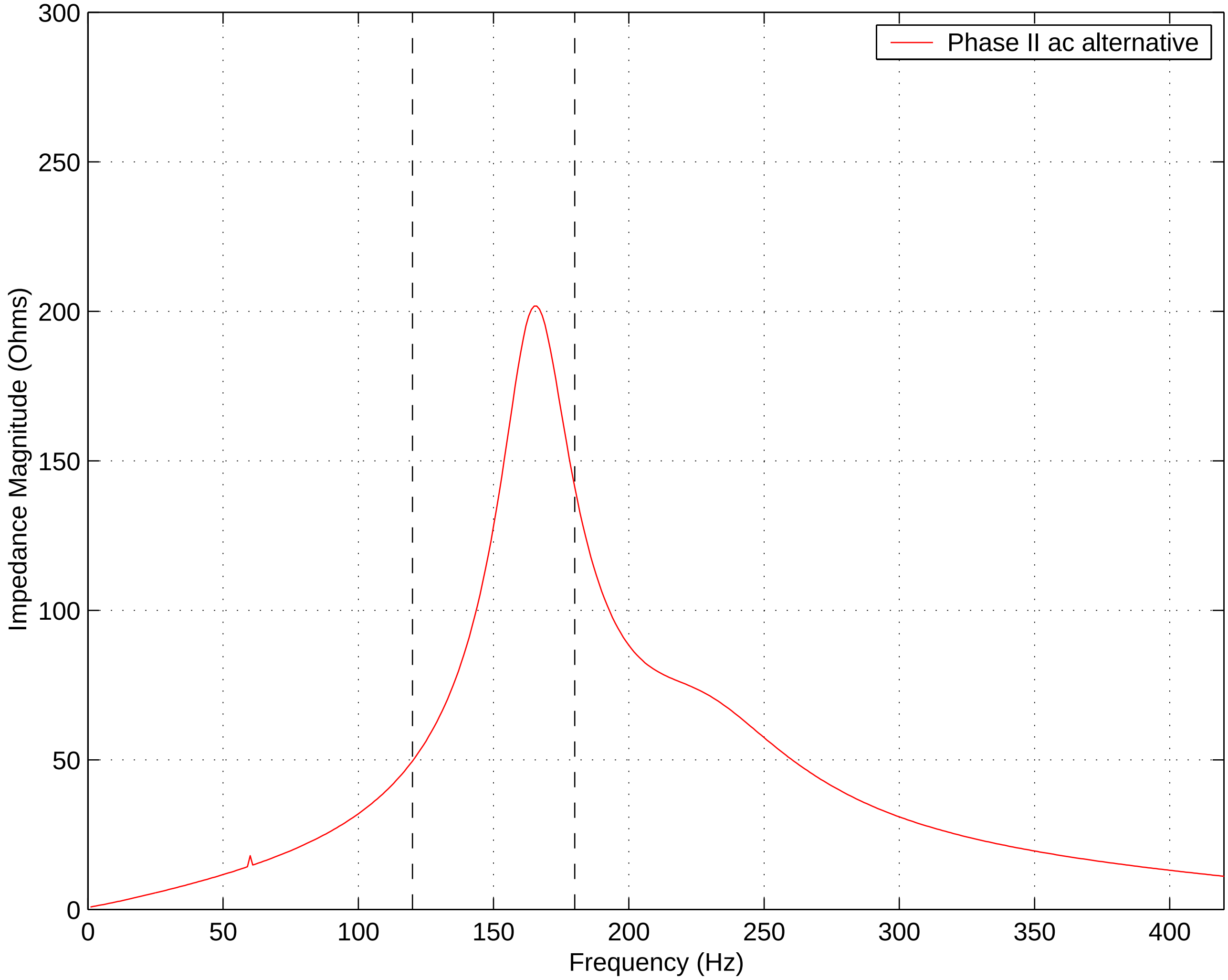


Figure D−58: Frequency Scan at Devon 115 kV − Cont 6

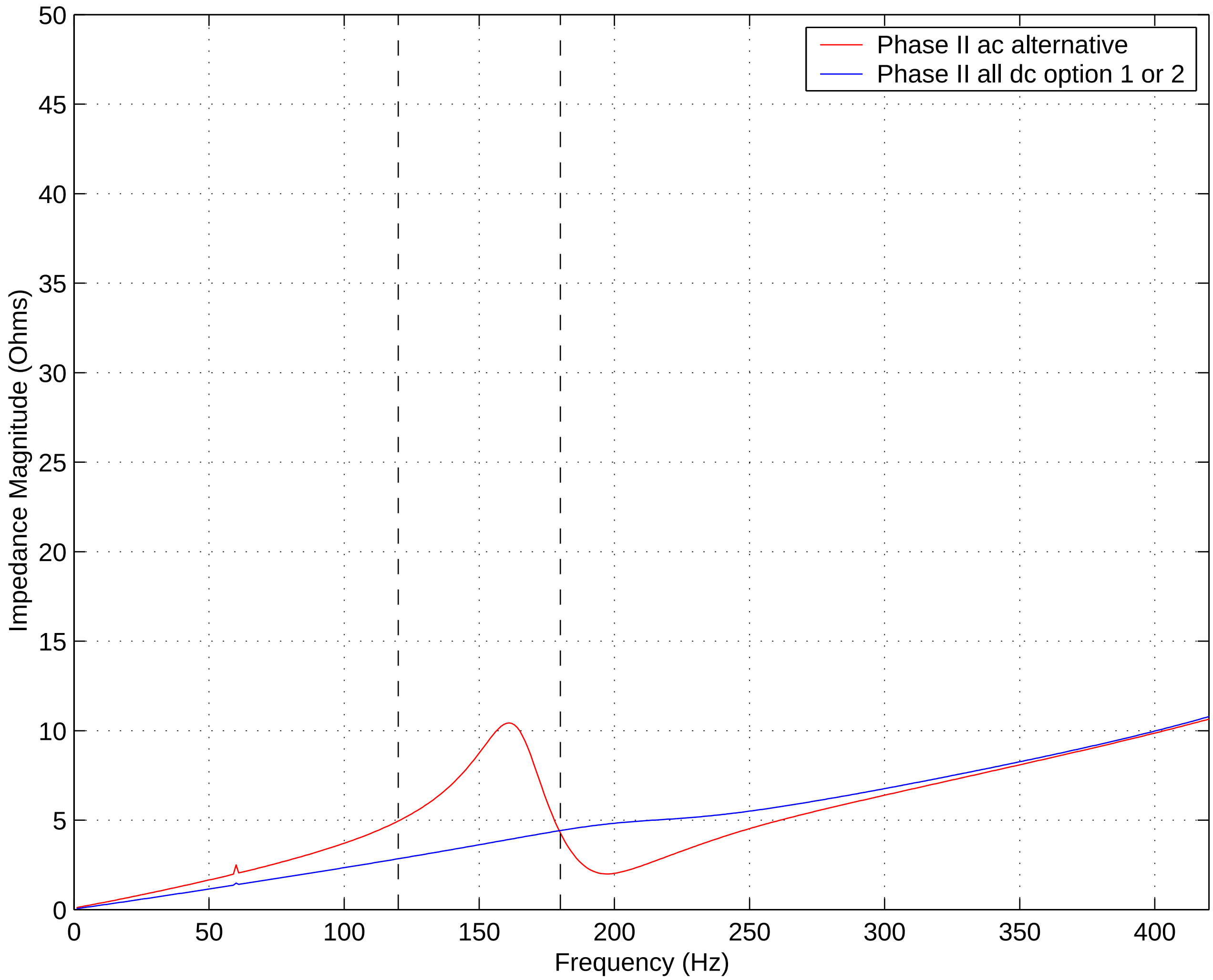
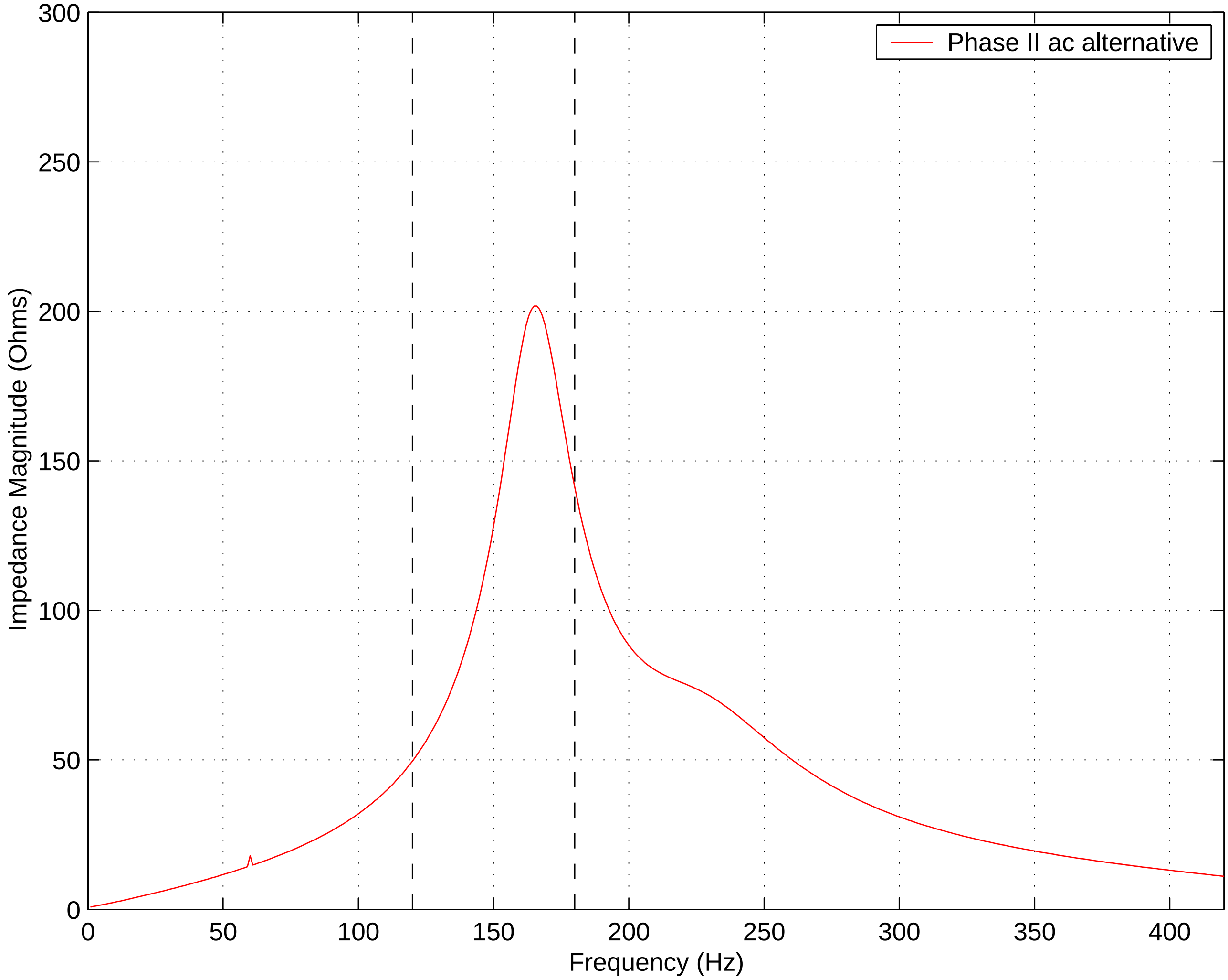


Figure D−59: Frequency Scan at Singer 345 kV − Cont 6



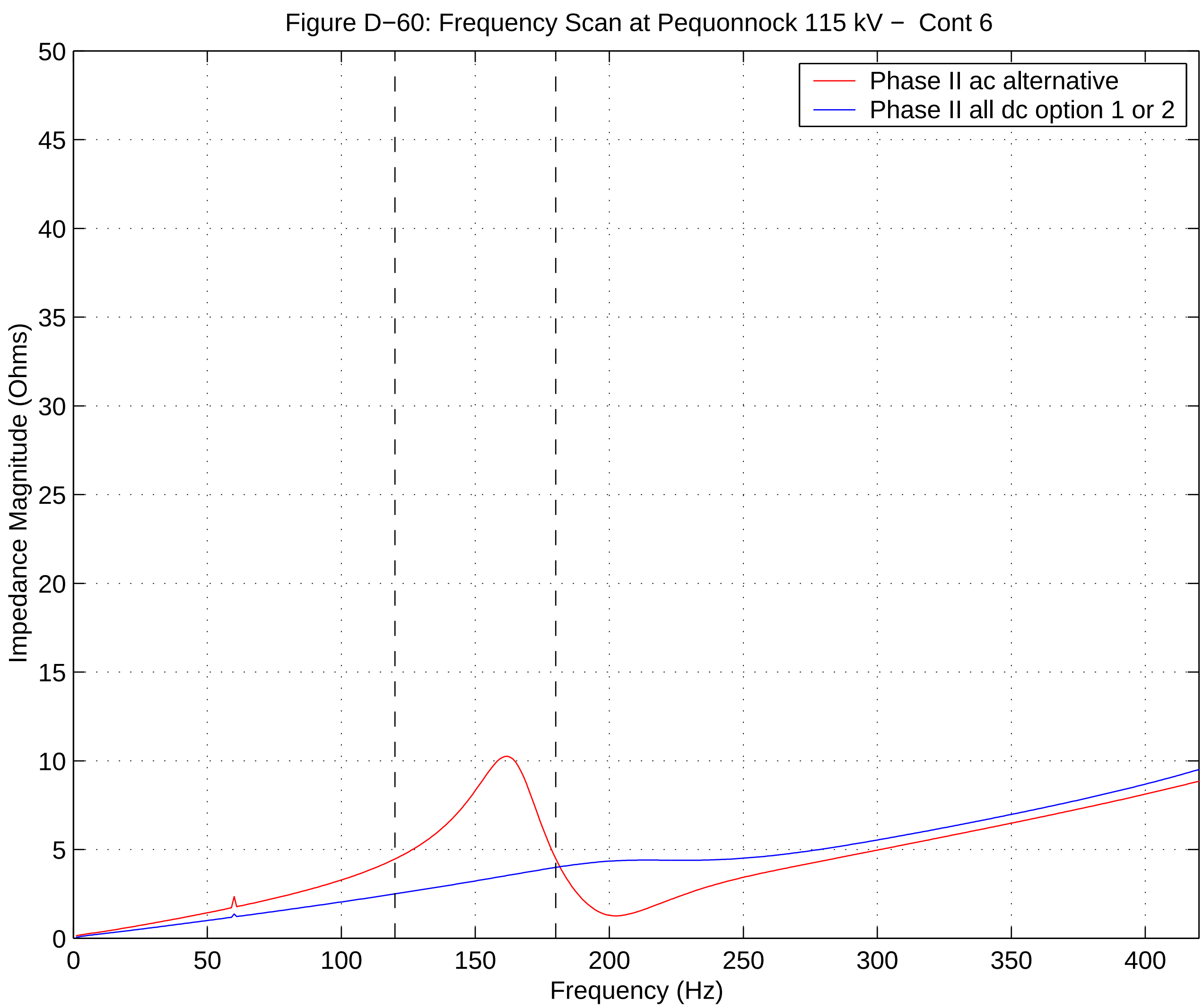


Figure D−60: Frequency Scan at Pequonnock 115 kV − Cont 6
Phase II ac alternative
Phase II all dc option 1 or 2
Impedance Magnitude (Ohms)
Frequency (Hz)
0
5
10
15
20
25
30
35
40
45
50
0
50
100
150
200
250
300
350
400

Figure D−61: Frequency Scan at Plumtree 345 kV − Cont 6

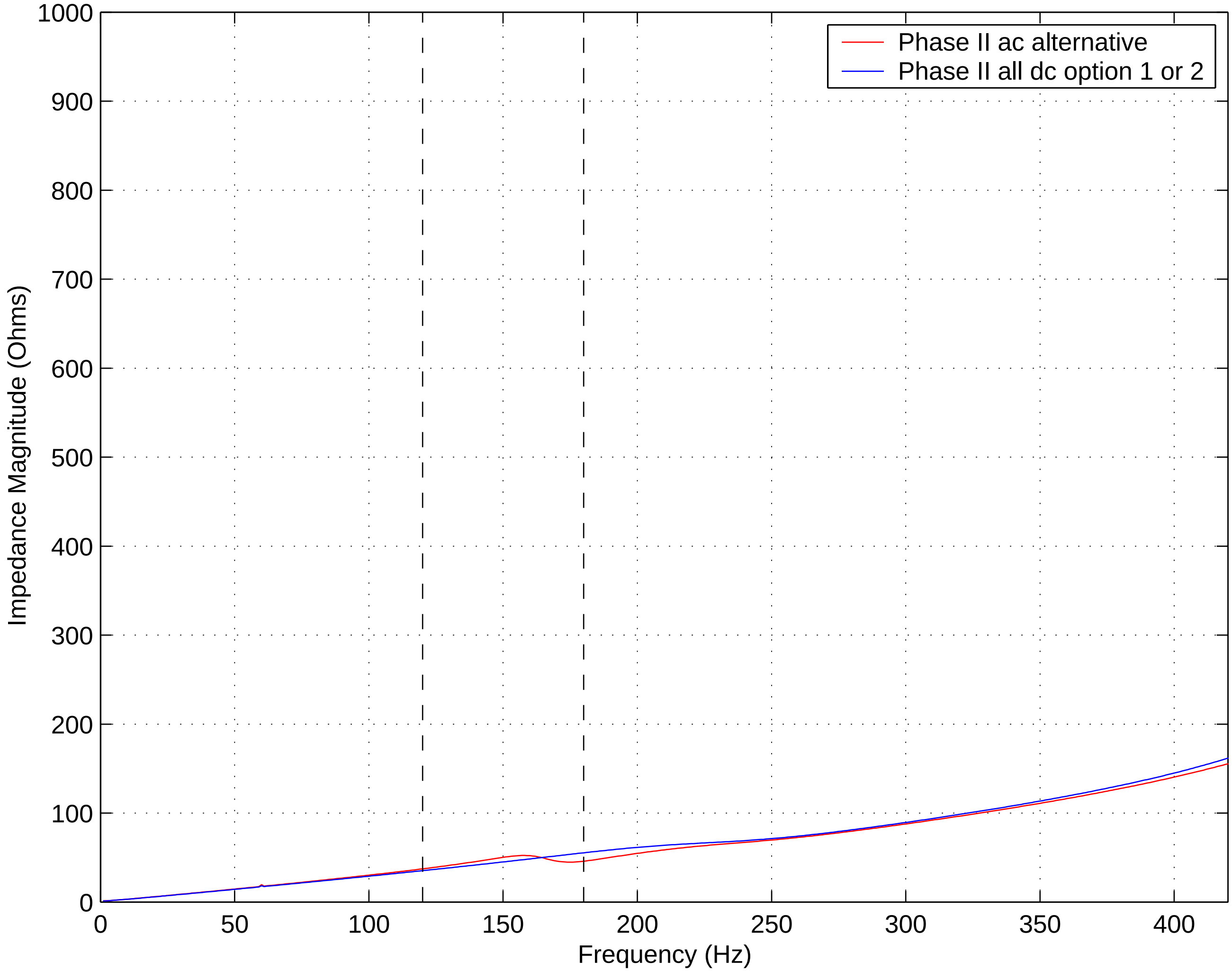
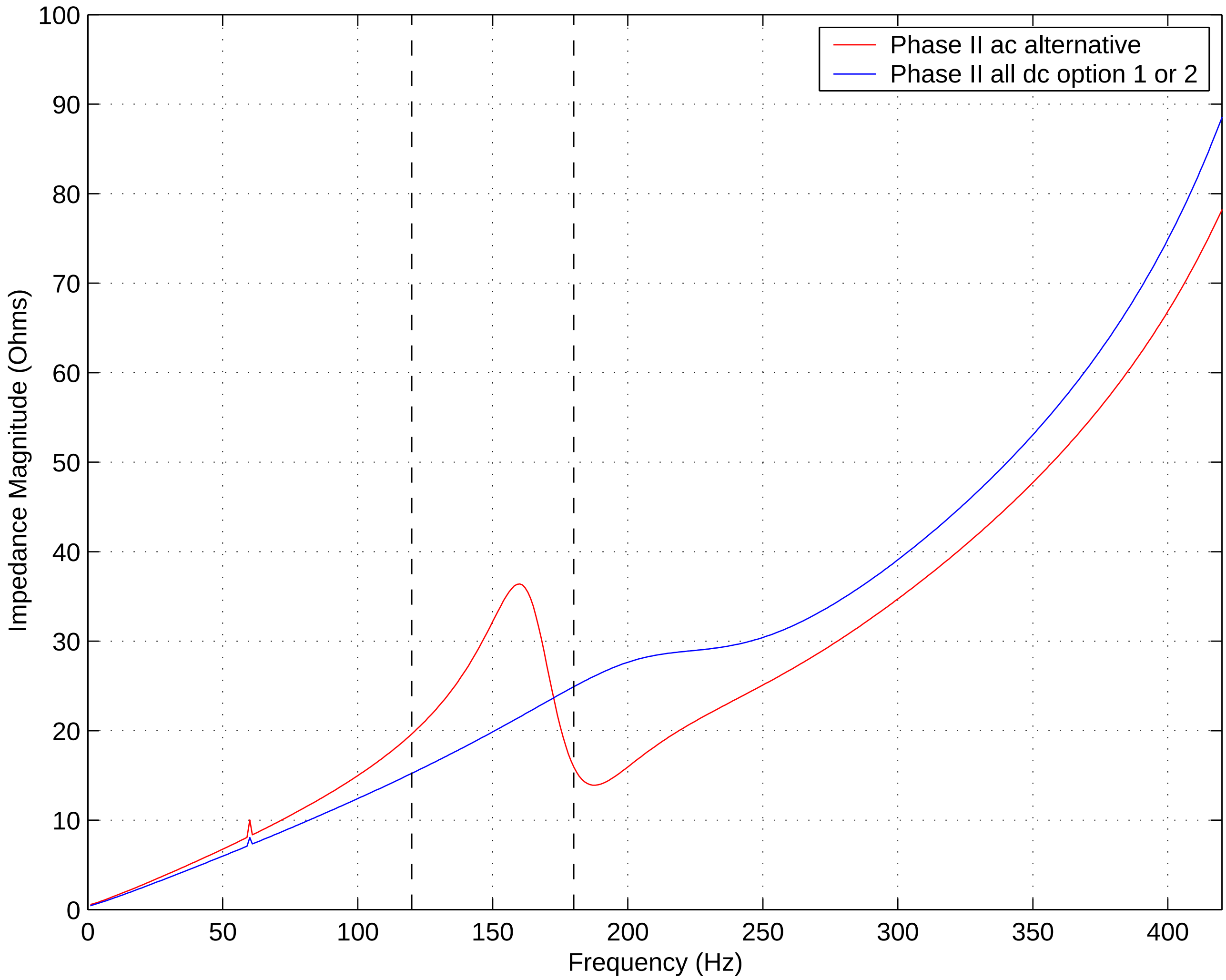


Figure D−62: Frequency Scan at Southington 345 kV − Cont 6



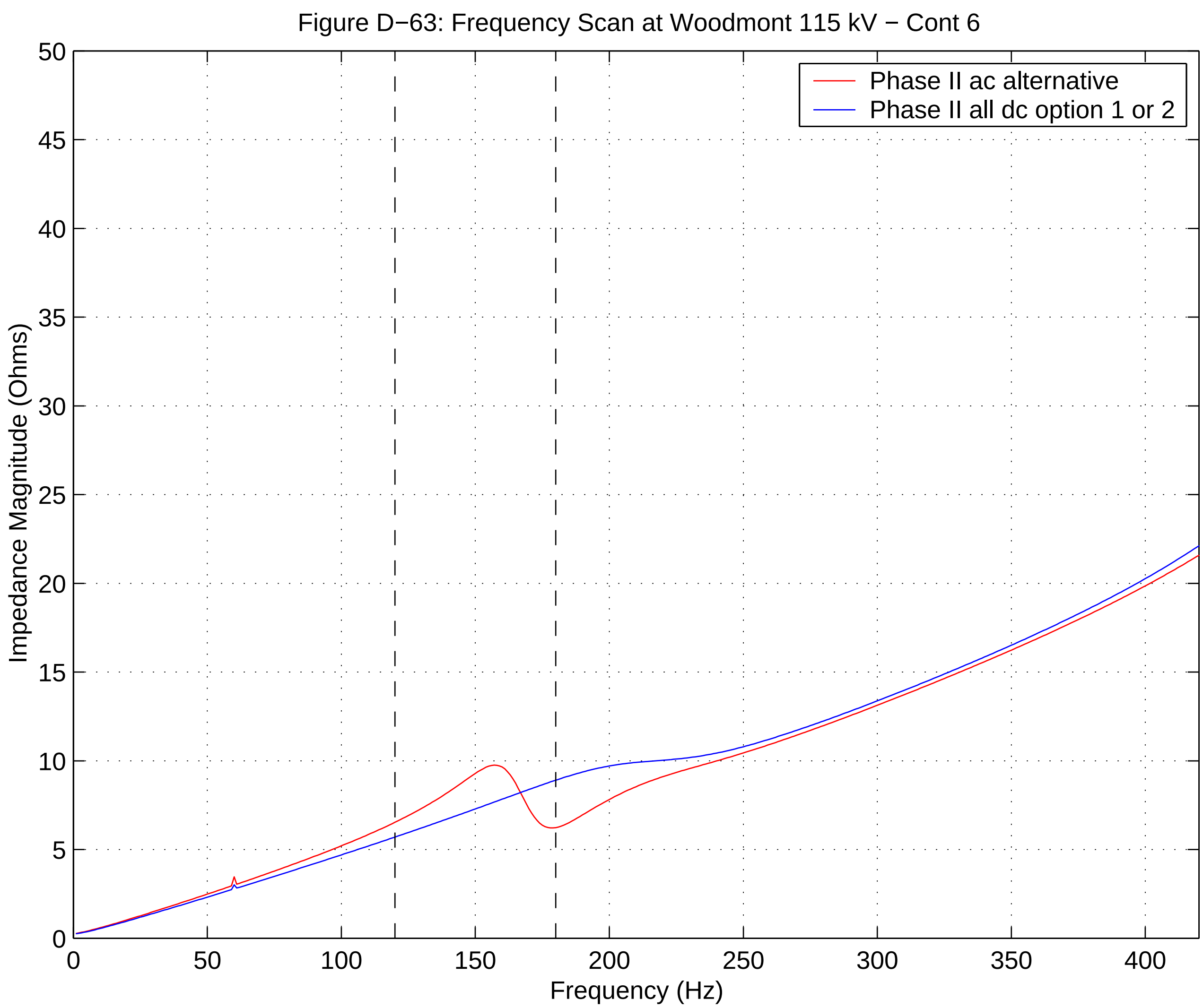


Figure D−63: Frequency Scan at Woodmont 115 kV − Cont 6
Phase II ac alternative
Phase II all dc option 1 or 2
Impedance Magnitude (Ohms)
Frequency (Hz)
0
5
10
15
20
25
30
35
40
45
50
0
50
100
150
200
250
300
350
400

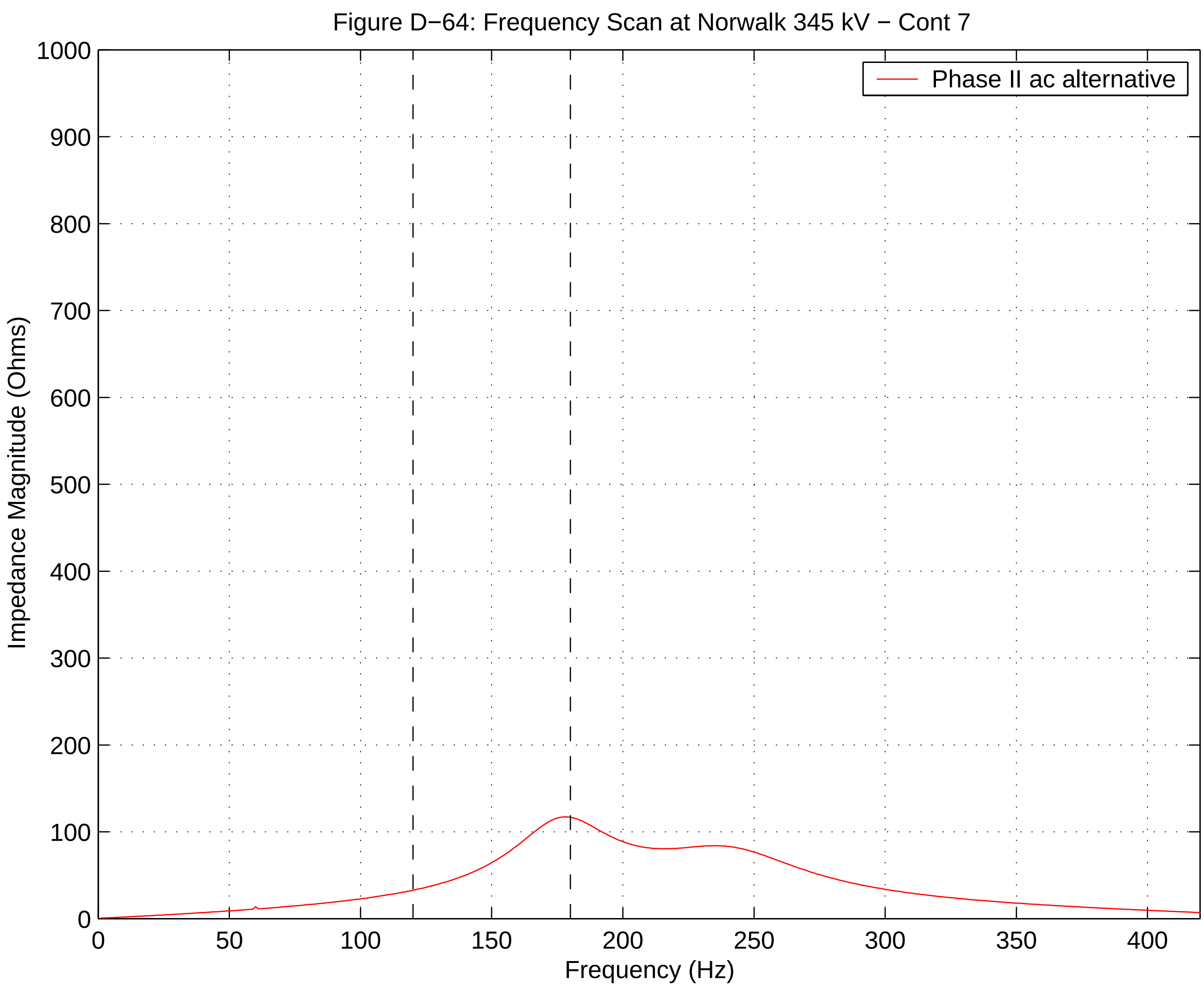
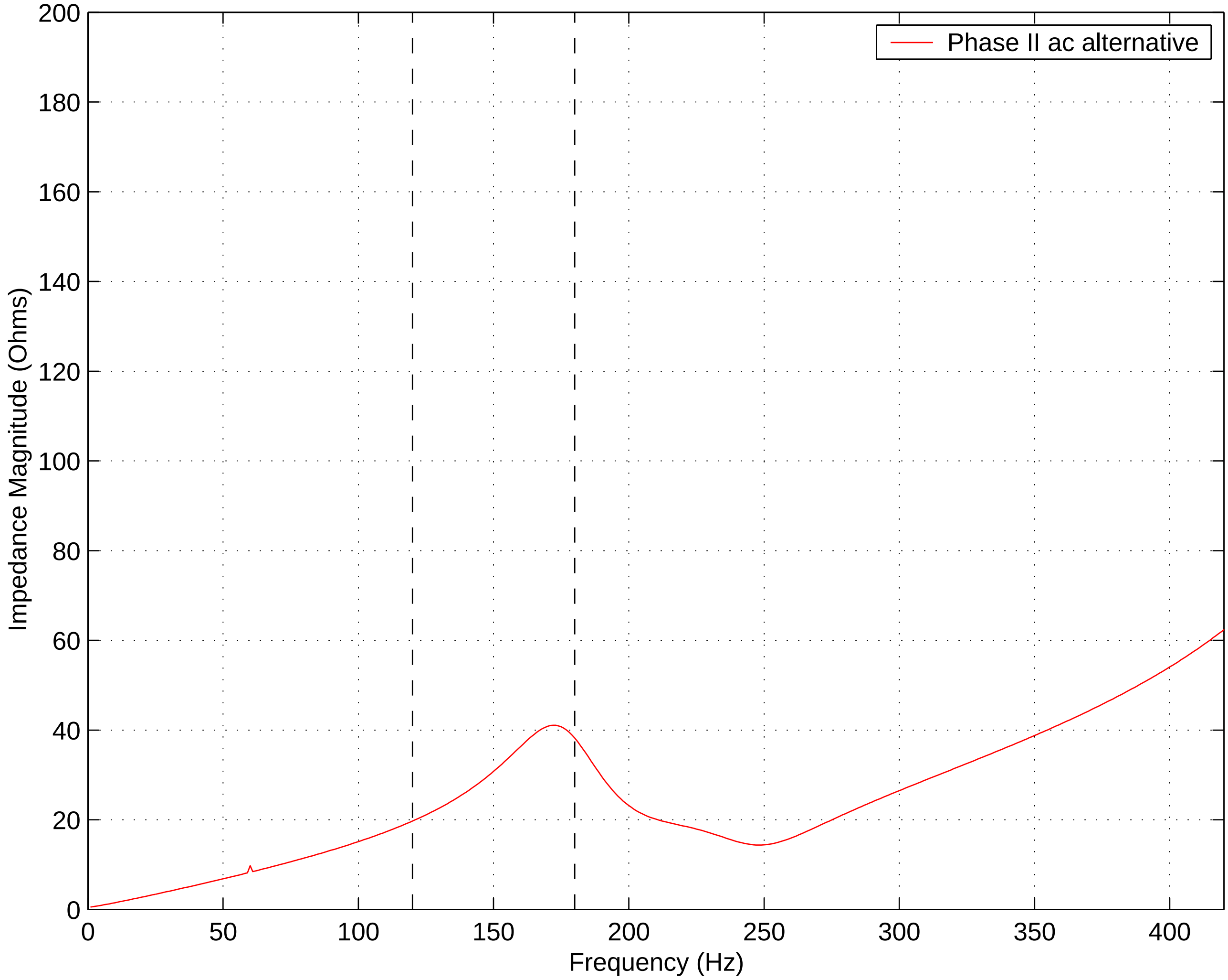


Figure D−64: Frequency Scan at Norwalk 345 kV − Cont 7
Phase II ac alternative
Impedance Magnitude (Ohms)
Frequency (Hz)
0
100
200
300
400
500
600
700
800
900
1000
0
50
100
150
200
250
300
350
400

Figure D−65: Frequency Scan at Beseck 345 kV − Cont 7



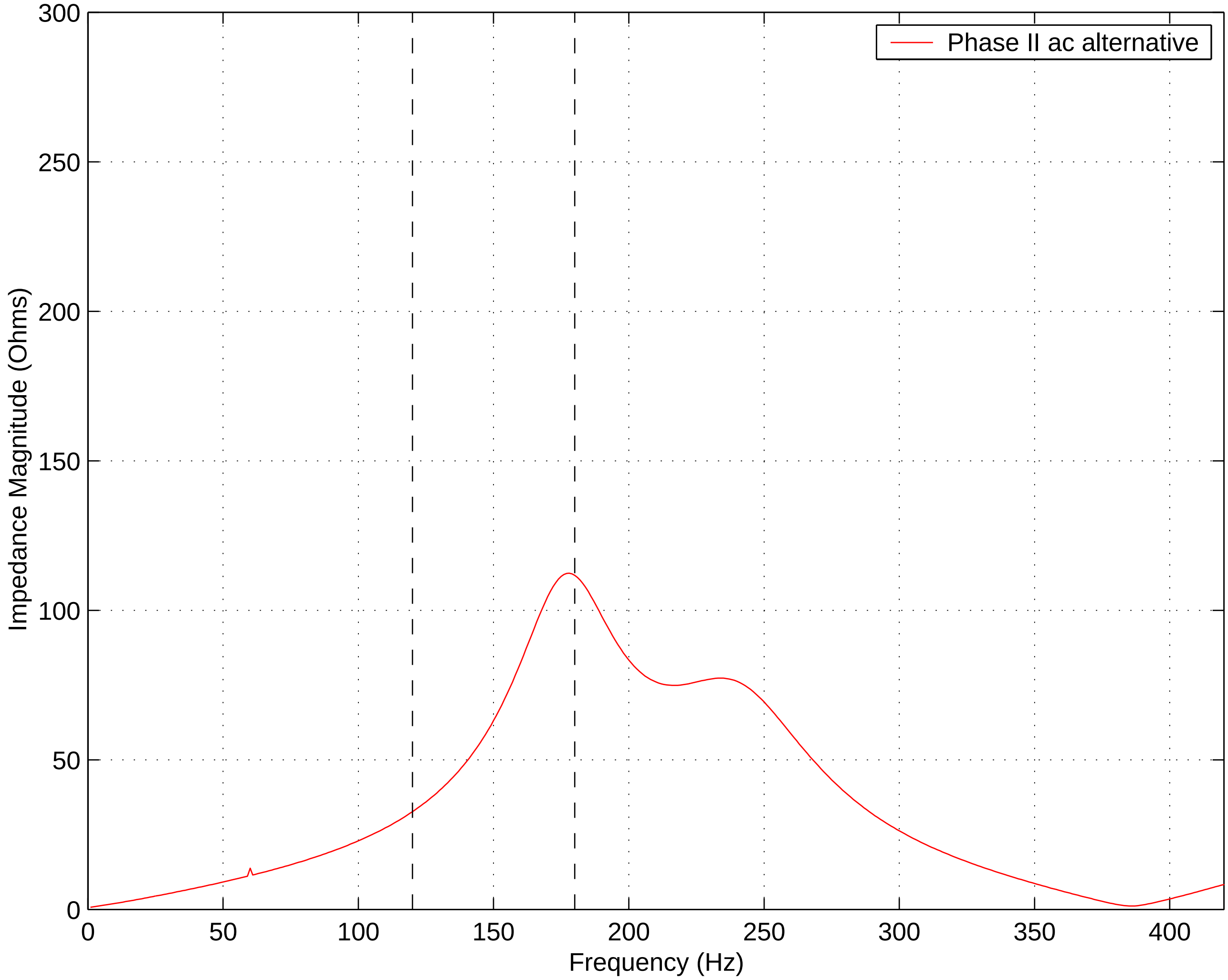


Figure D−66: Frequency Scan at Devon 345 kV − Cont 7

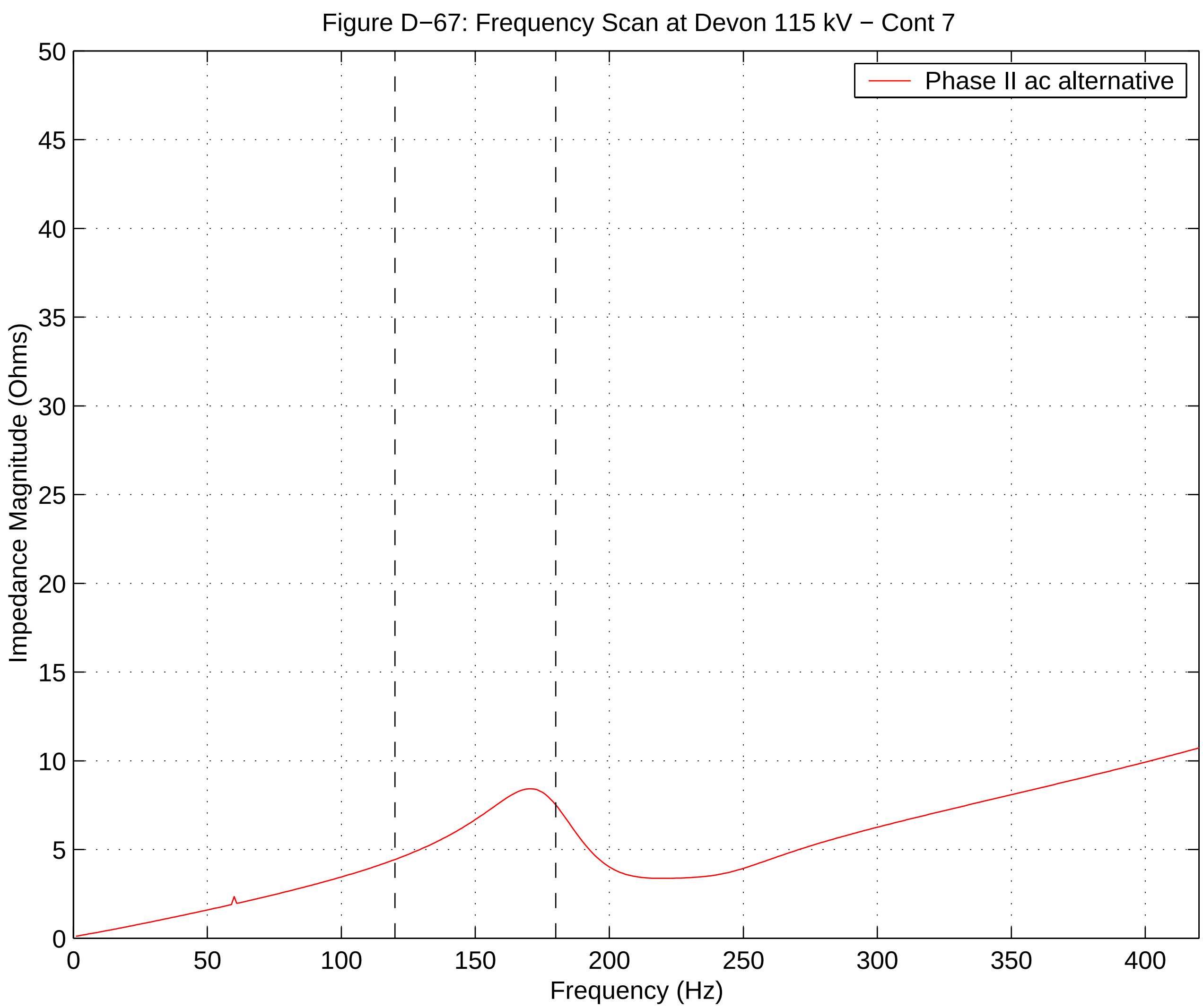


Figure D−67: Frequency Scan at Devon 115 kV − Cont 7
Phase II ac alternative
Impedance Magnitude (Ohms)
Frequency (Hz)
0
5
10
15
20
25
30
35
40
45
50
0
50
100
150
200
250
300
350
400

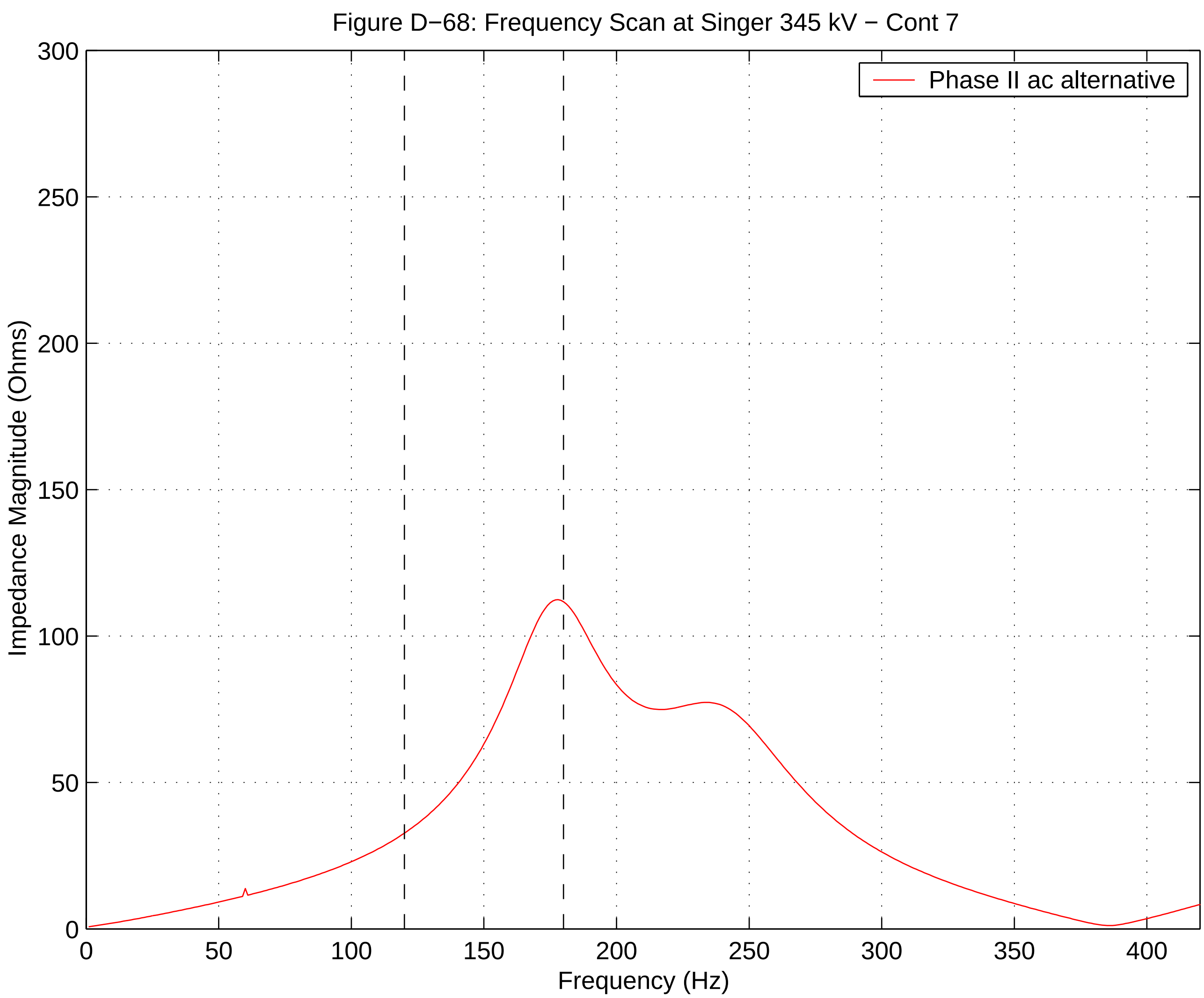


Figure D−68: Frequency Scan at Singer 345 kV − Cont 7
Phase II ac alternative
Impedance Magnitude (Ohms)
Frequency (Hz)
0
50
100
150
200
250
300
350
400

Figure D−69: Frequency Scan at Pequonnock 115 kV − Cont 7

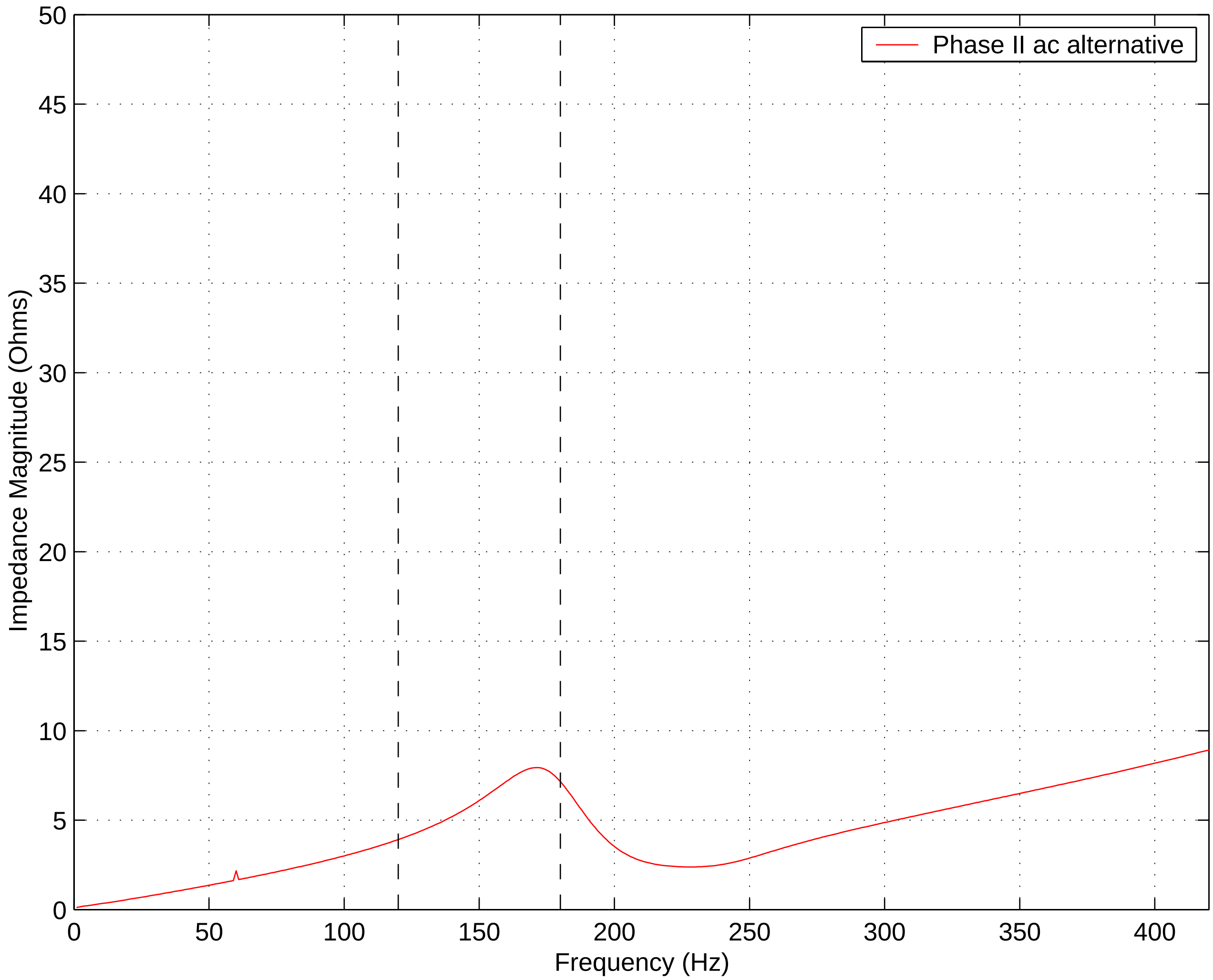


Figure D−70: Frequency Scan at Plumtree 345 kV − Cont 7

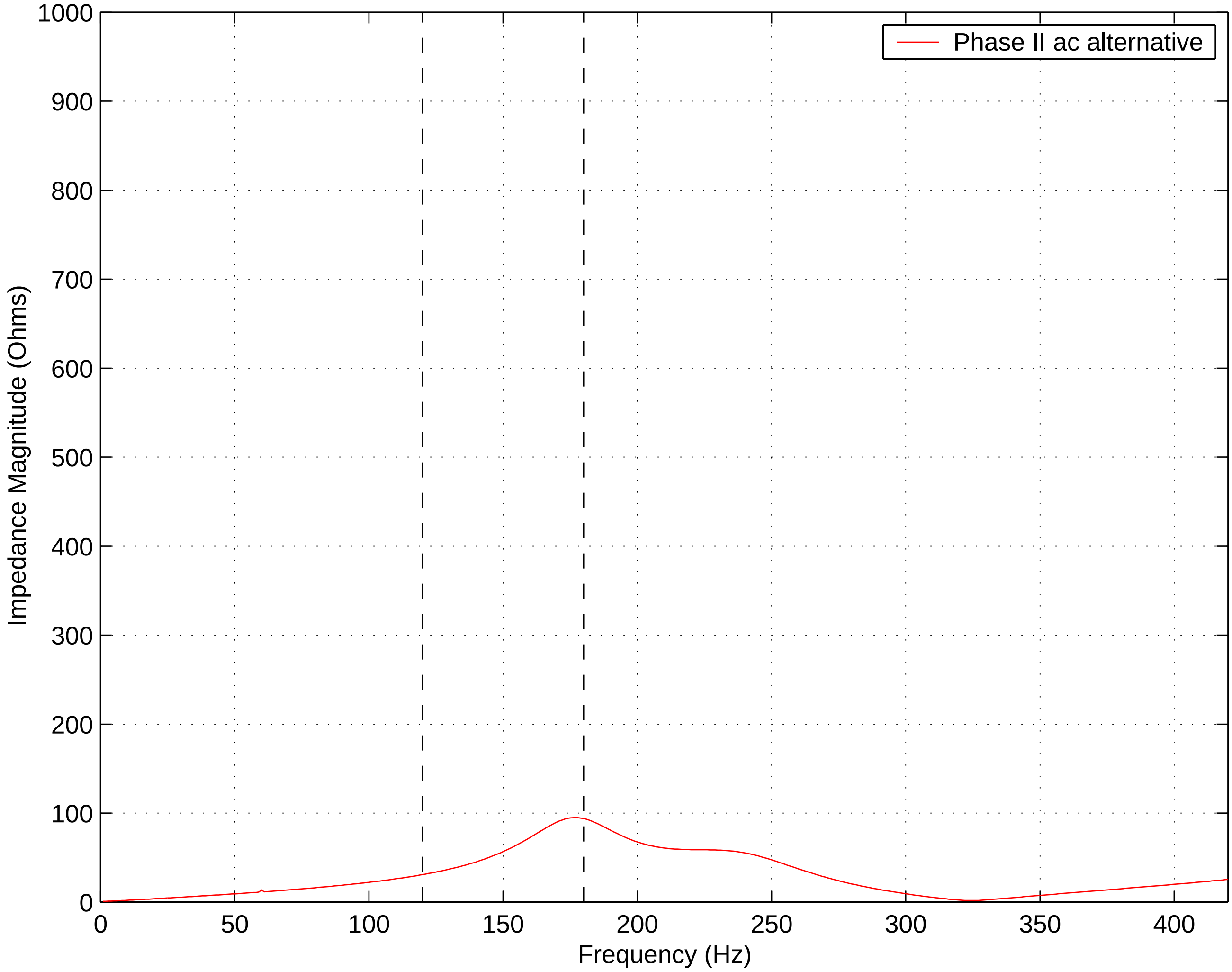


Figure D−71: Frequency Scan at Southington 345 kV − Cont 7

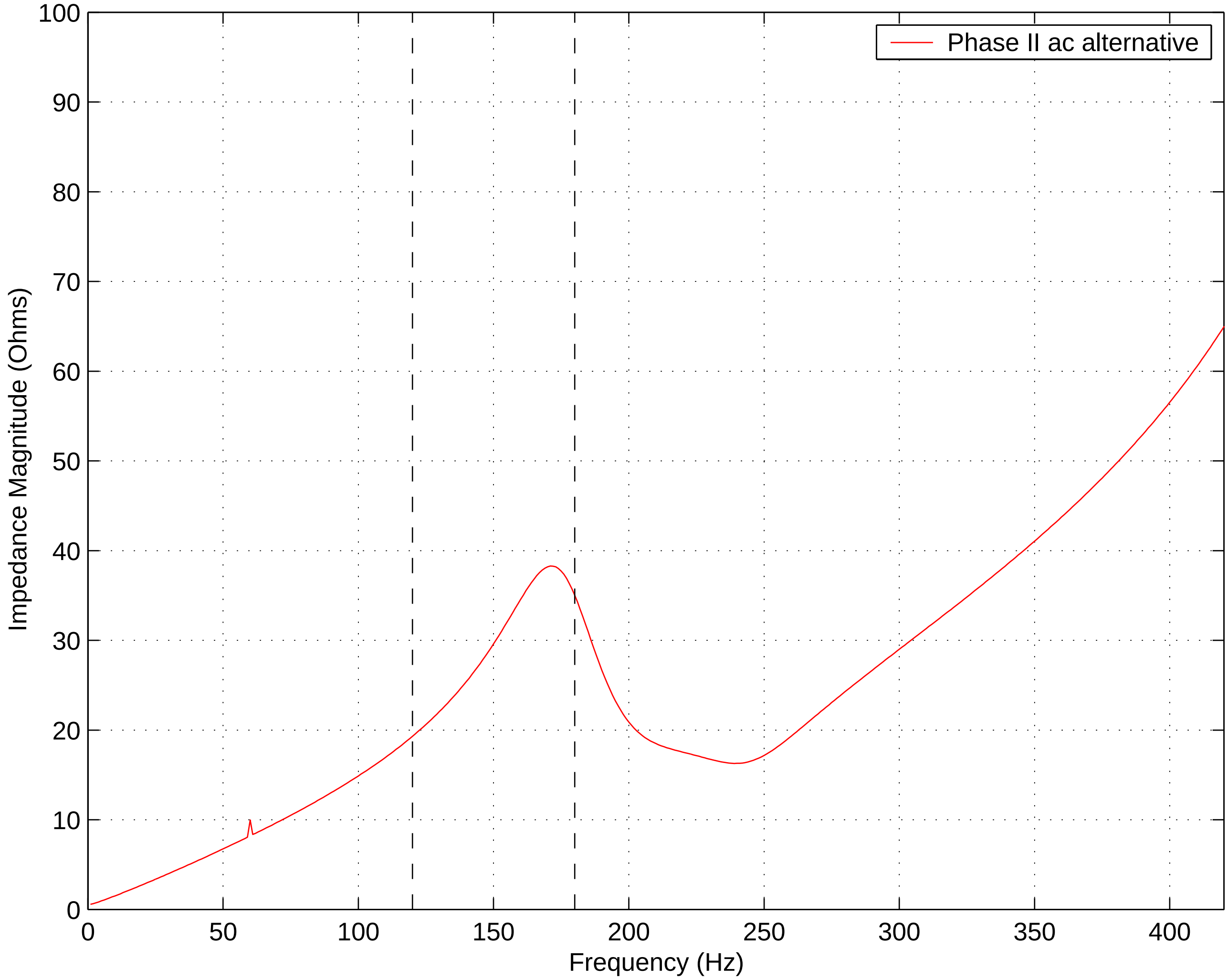


Figure D−72: Frequency Scan at Woodmont 115 kV − Cont 7

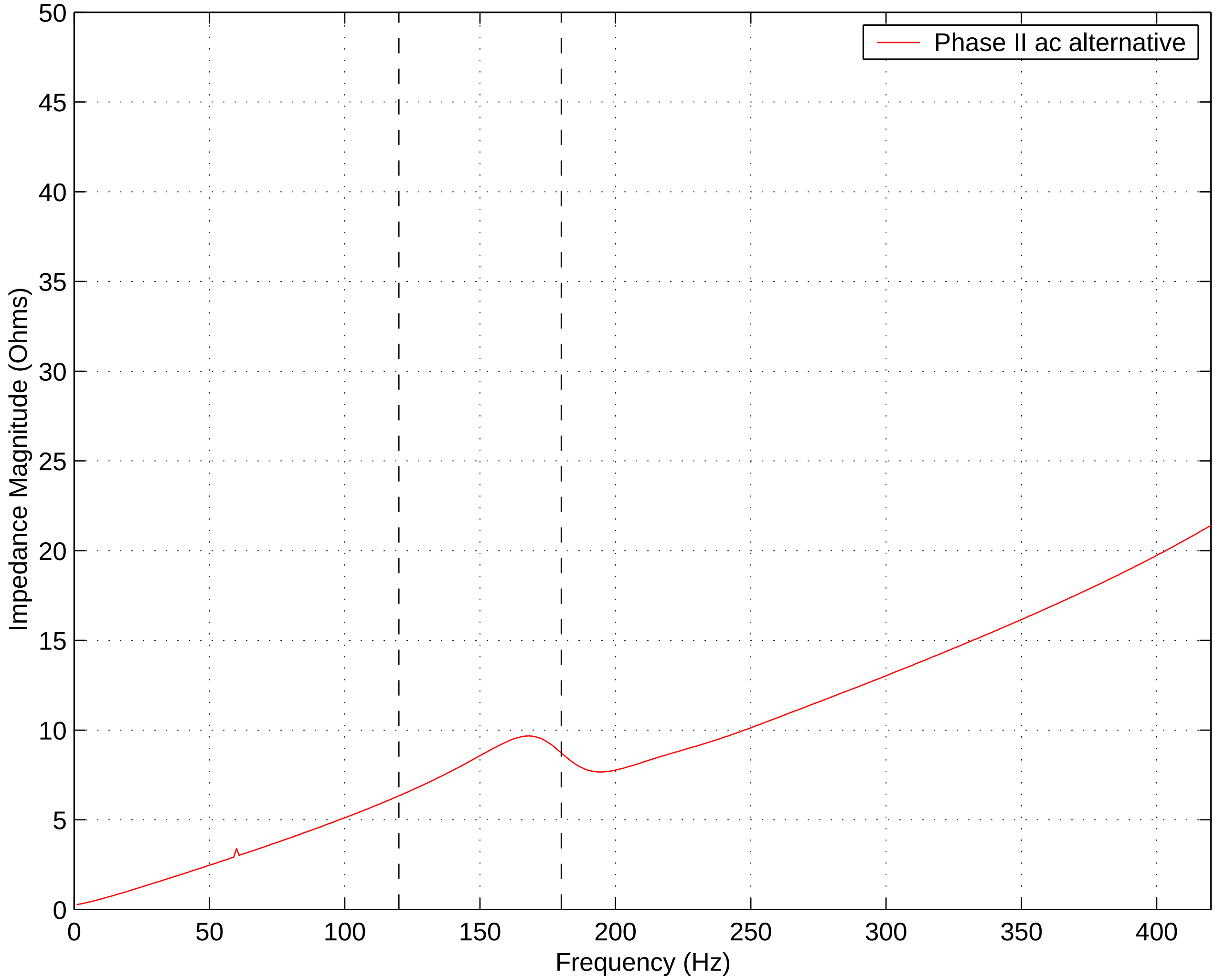
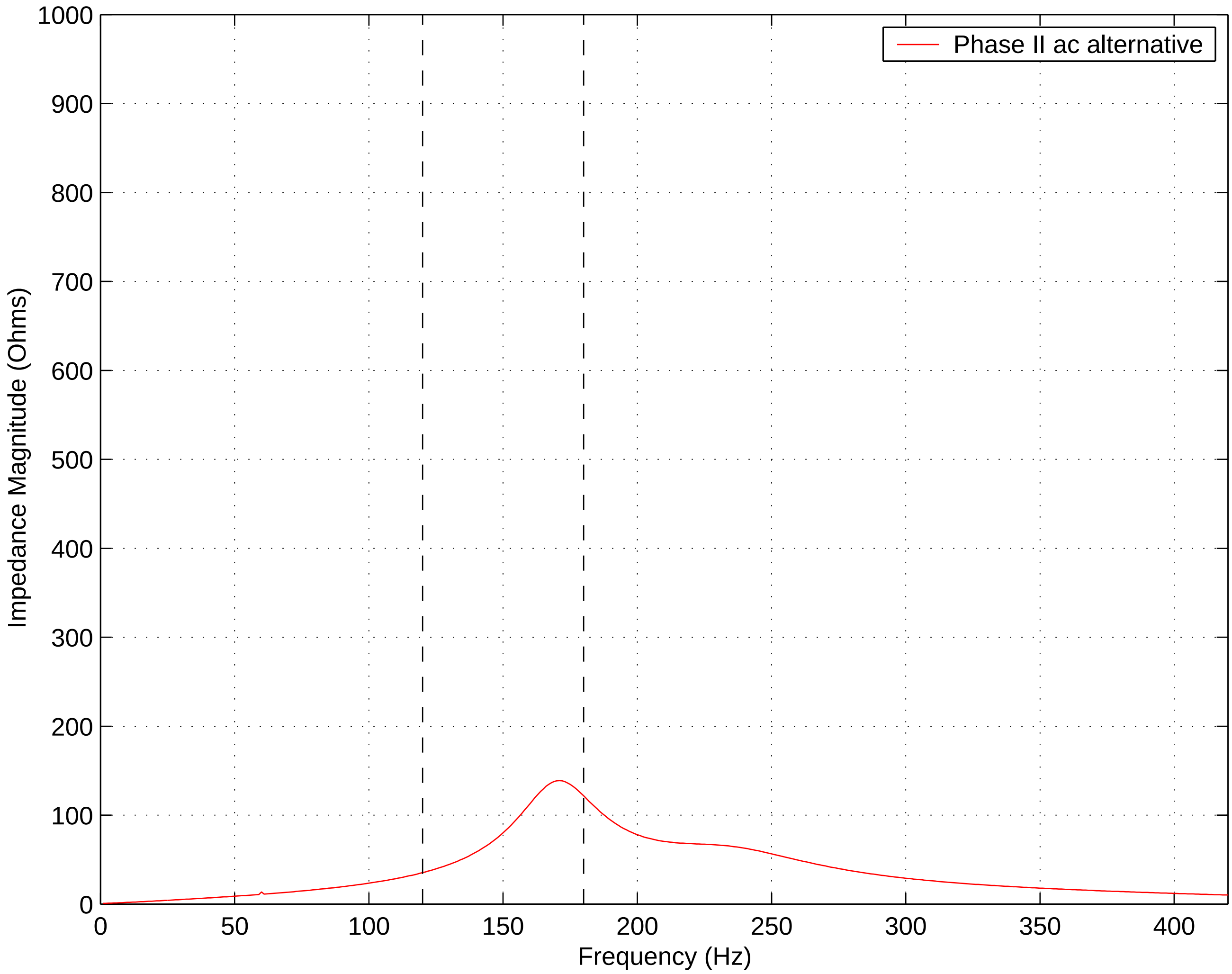


Figure D−73: Frequency Scan at Norwalk 345 kV − Cont 8



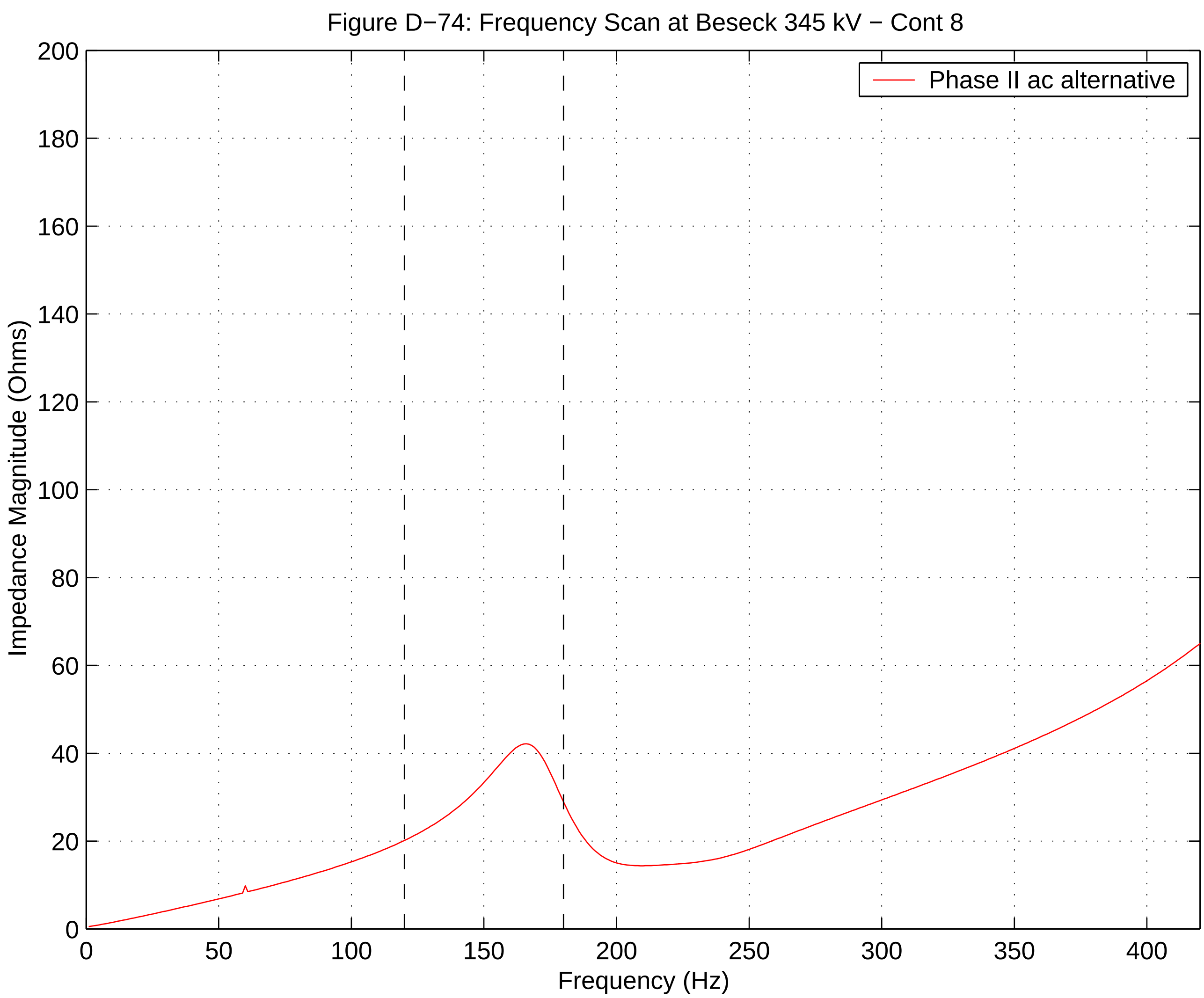


Figure D−74: Frequency Scan at Beseck 345 kV − Cont 8
Phase II ac alternative
Impedance Magnitude (Ohms)
Frequency (Hz)
0
20
40
60
80
100
120
140
160
180
200
0
50
100
150
200
250
300
350
400

Figure D−75: Frequency Scan at Devon 345 kV − Cont 8

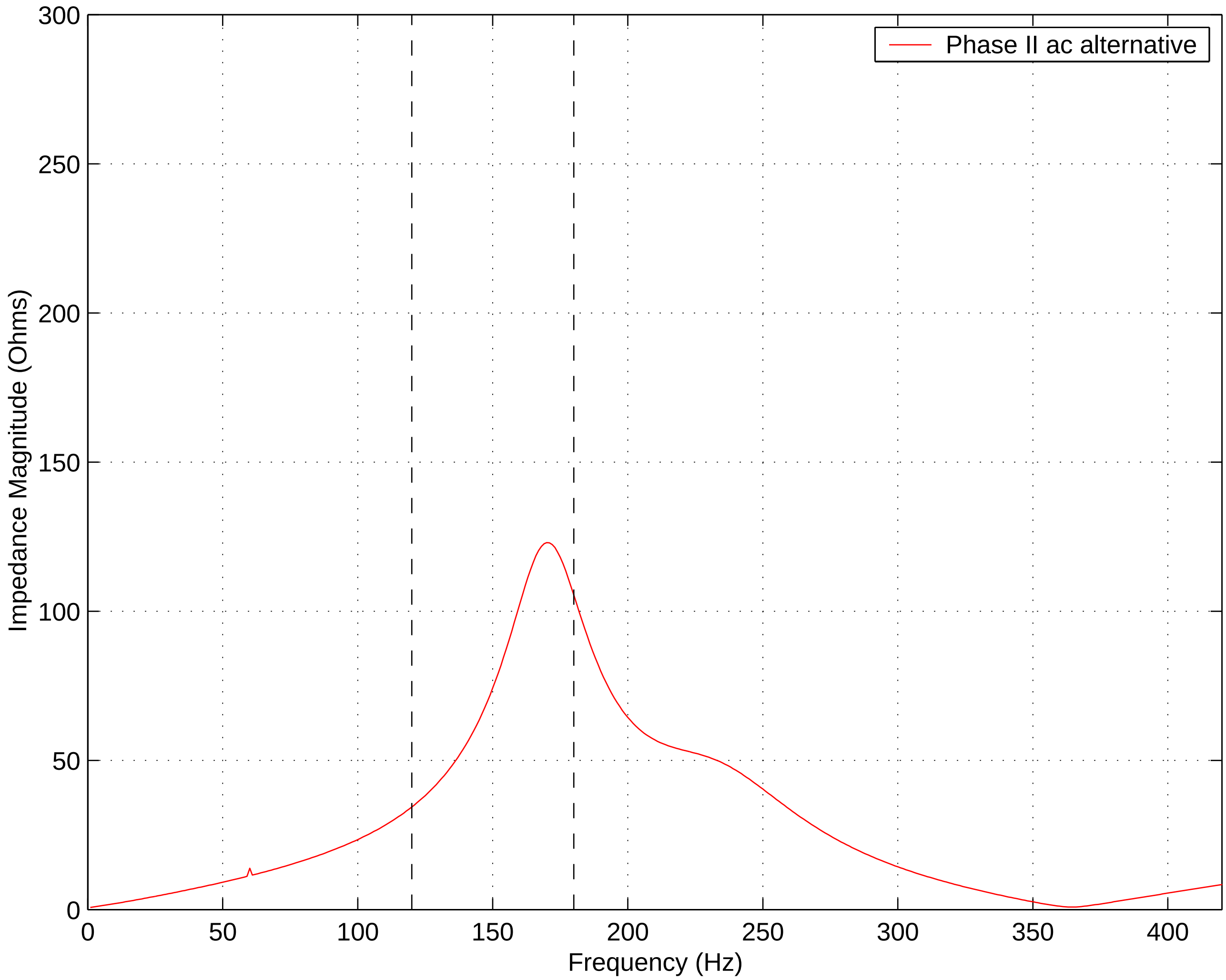
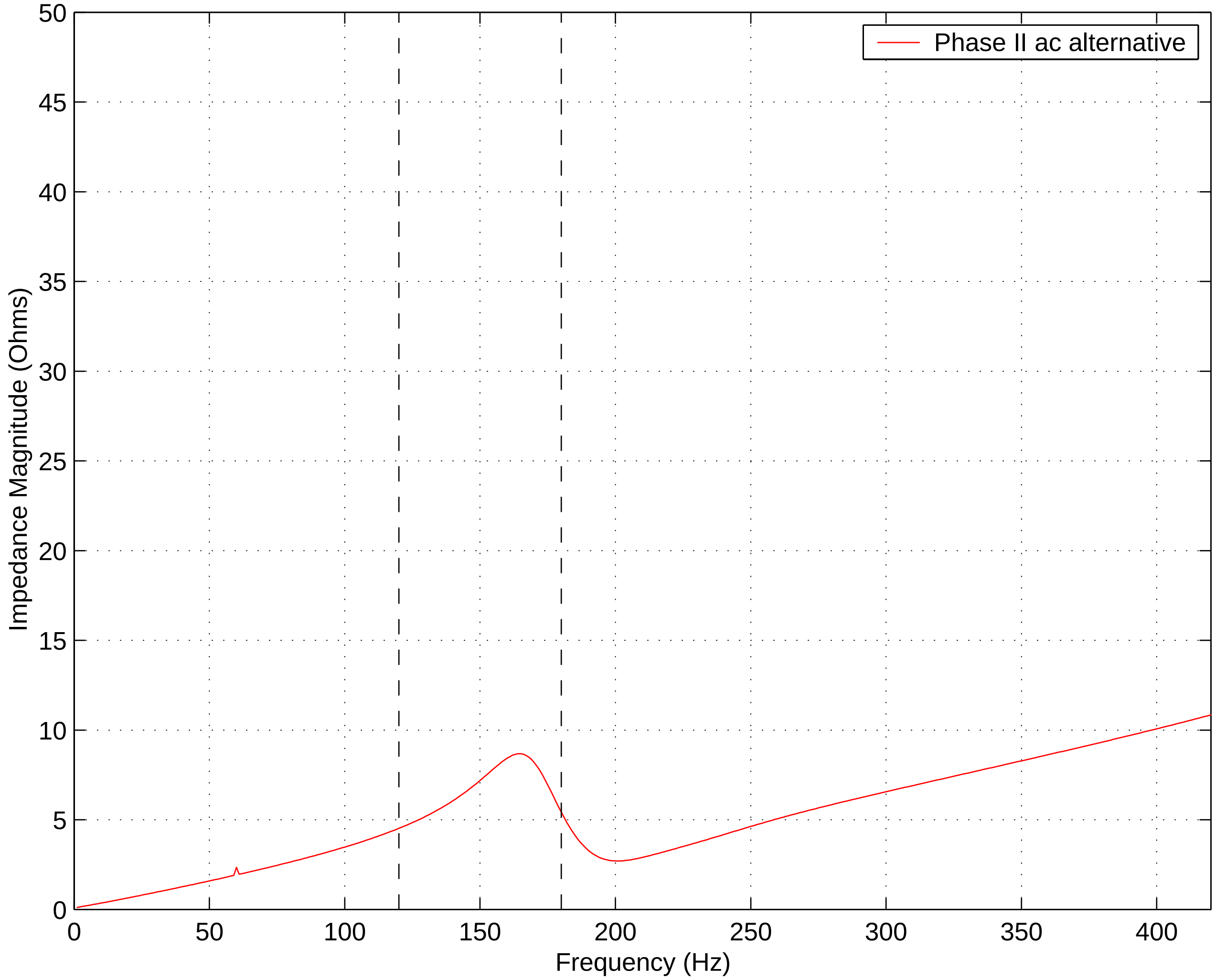


Figure D−76: Frequency Scan at Devon 115 kV − Cont 8



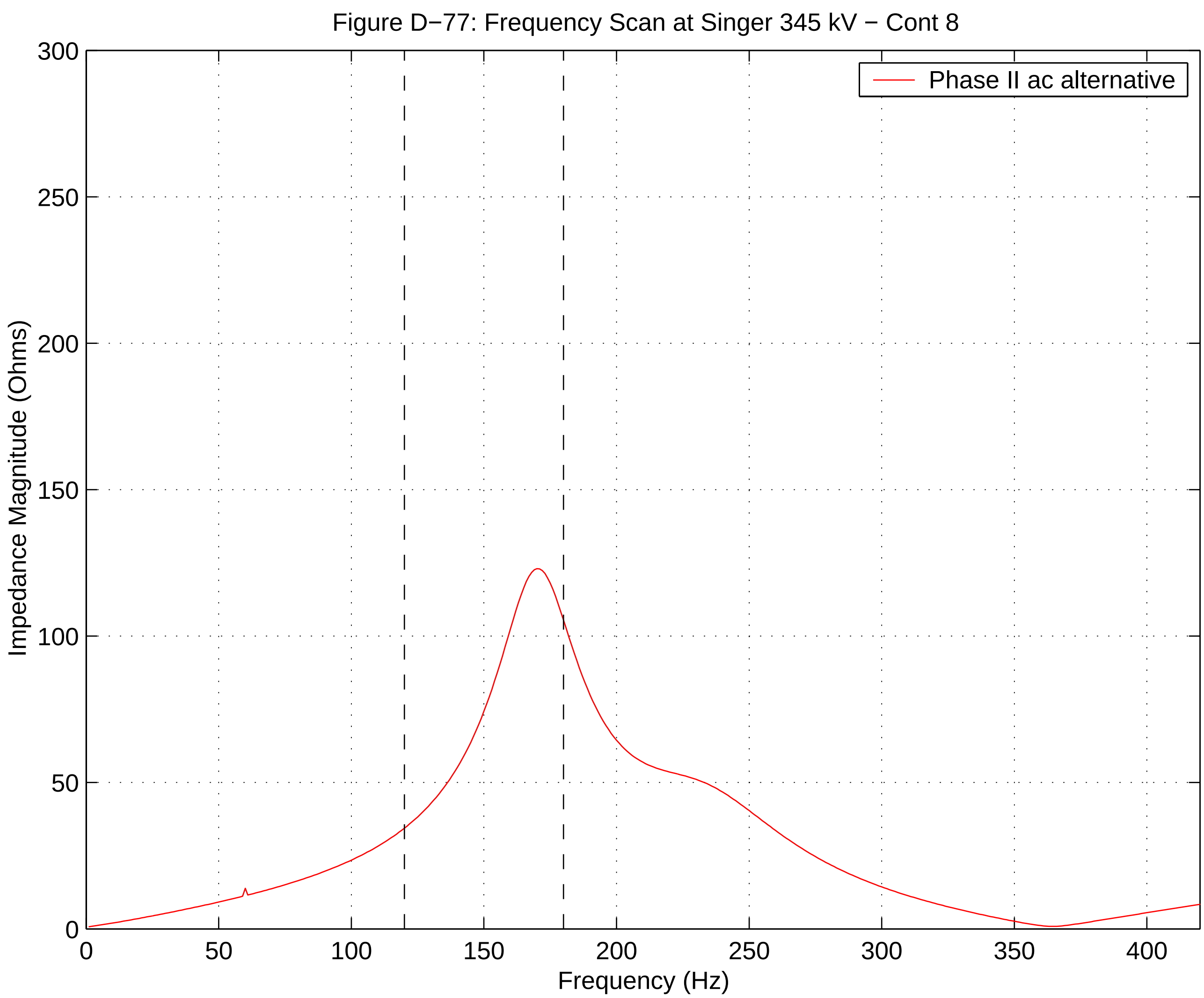


Figure D−77: Frequency Scan at Singer 345 kV − Cont 8
Phase II ac alternative
Impedance Magnitude (Ohms)
Frequency (Hz)
0
50
100
150
200
250
300
350
400

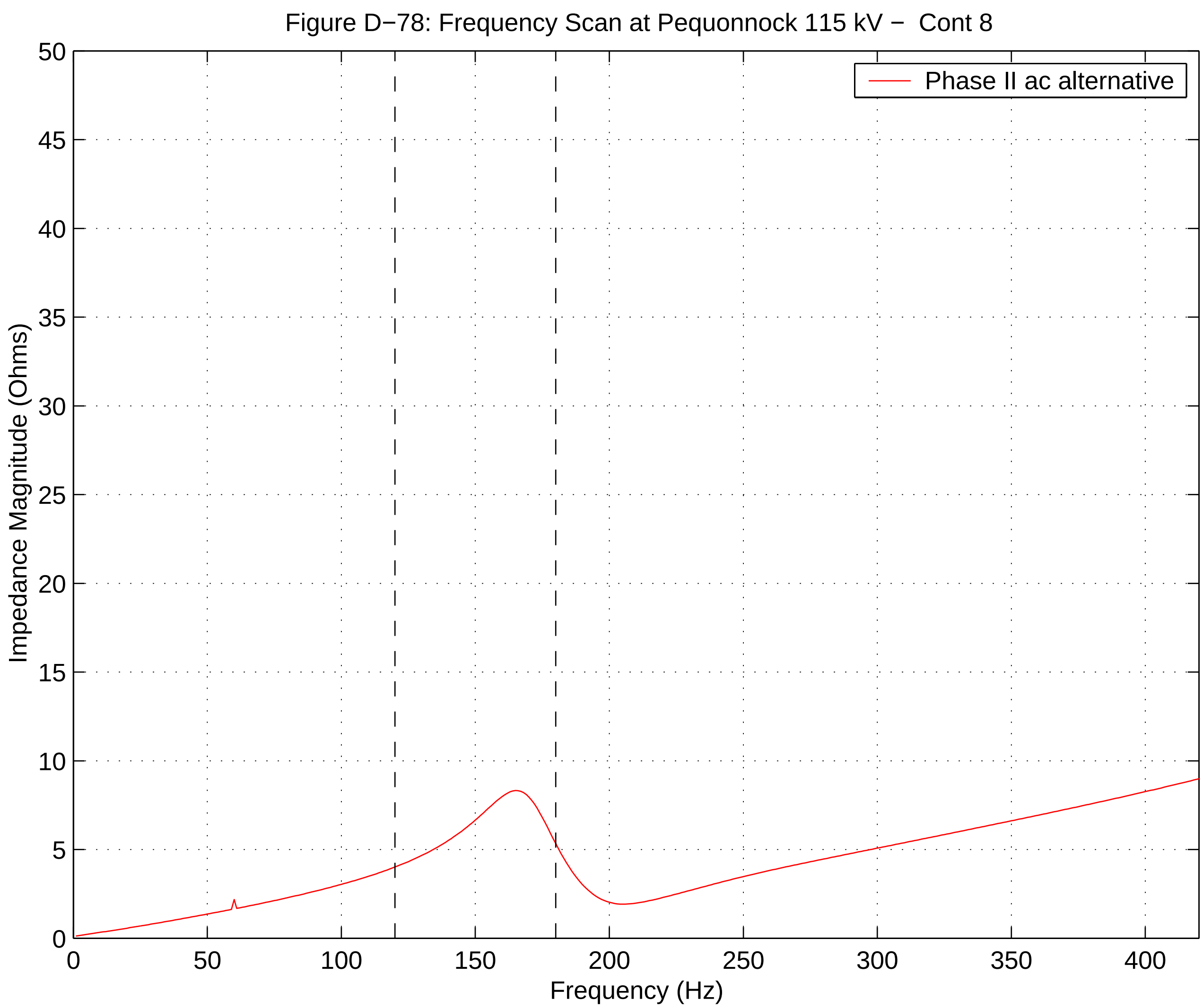
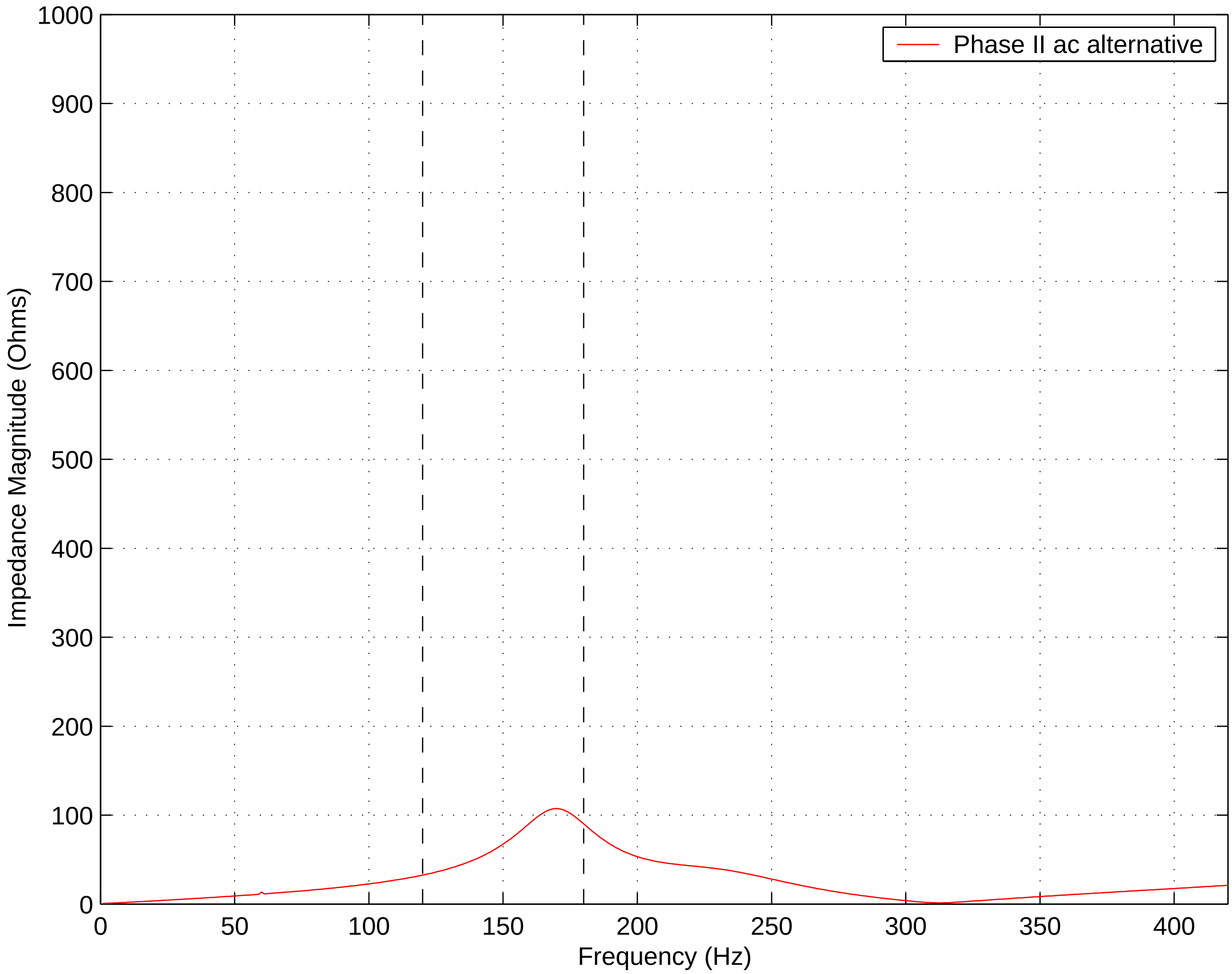


Figure D−78: Frequency Scan at Pequonnock 115 kV − Cont 8
Phase II ac alternative
Impedance Magnitude (Ohms)
Frequency (Hz)
0
5
10
15
20
25
30
35
40
45
50
0
50
100
150
200
250
300
350
400

Figure D−79: Frequency Scan at Plumtree 345 kV − Cont 8



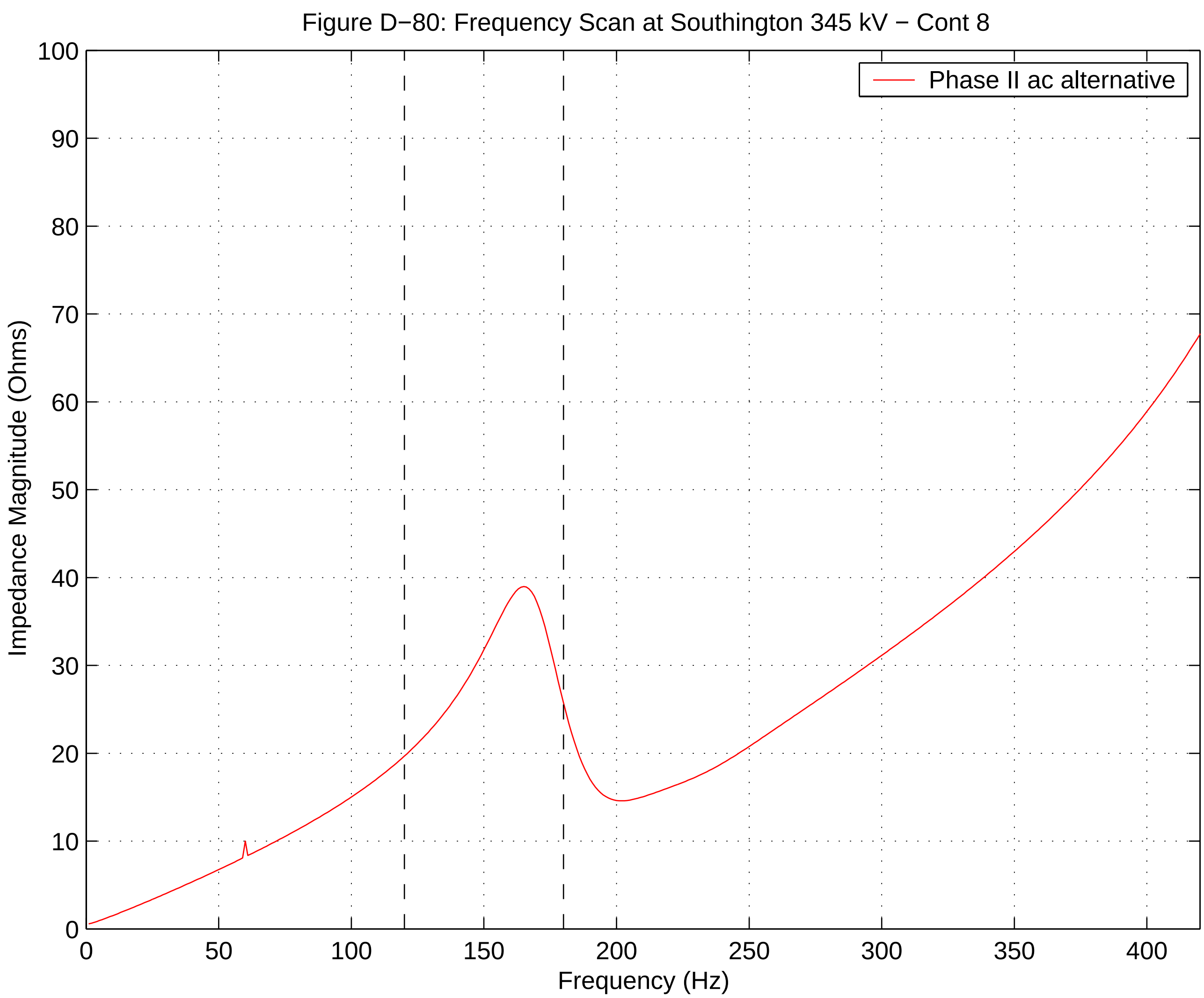
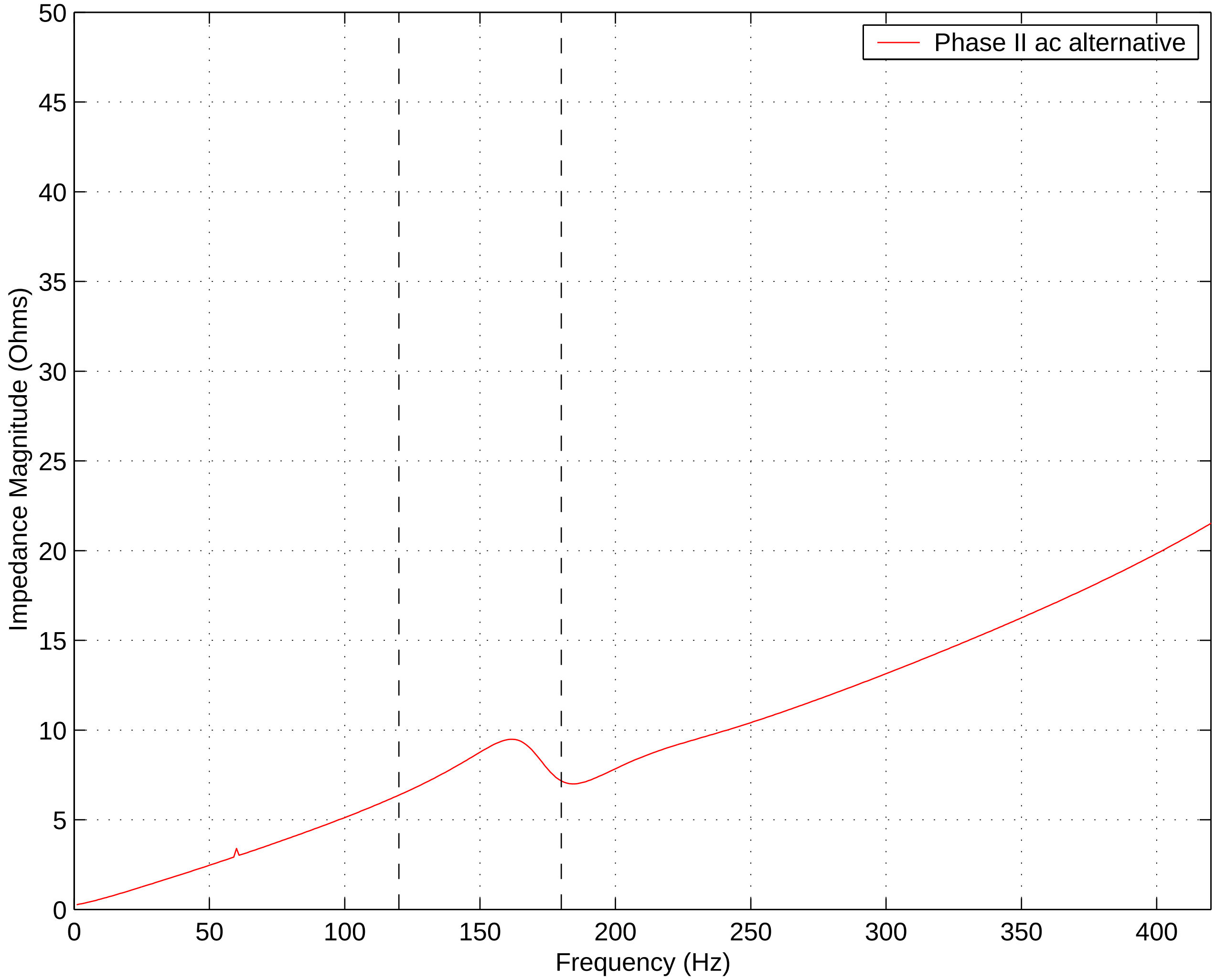


Figure D−80: Frequency Scan at Southington 345 kV − Cont 8
Phase II ac alternative
Impedance Magnitude (Ohms)
Frequency (Hz)
0
10
20
30
40
50
60
70
80
90
100
0
50
100
150
200
250
300
350
400

Figure D−81: Frequency Scan at Woodmont 115 kV − Cont 8



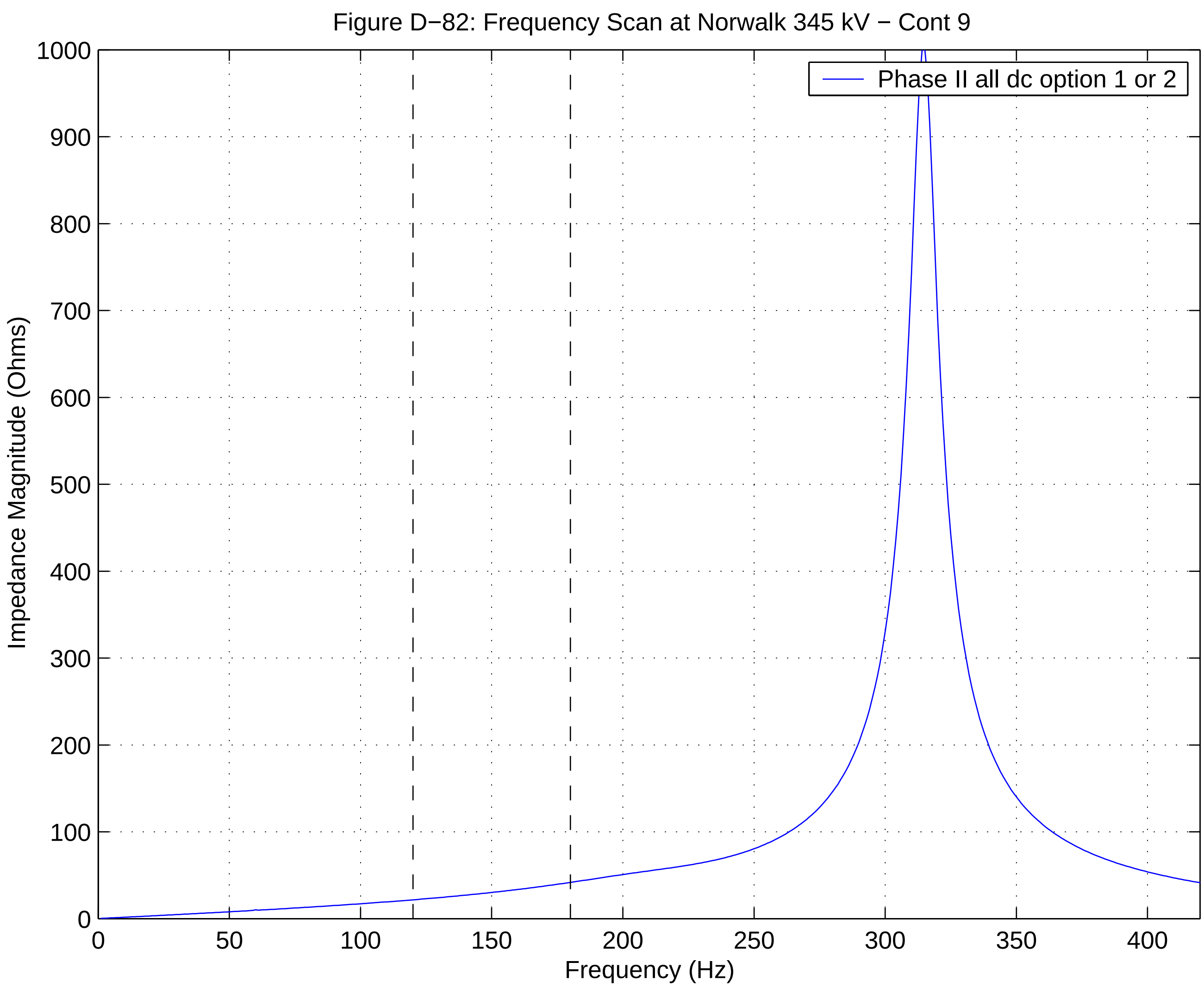


Figure D−82: Frequency Scan at Norwalk 345 kV − Cont 9
Phase II all dc option 1 or 2
Impedance Magnitude (Ohms)
Frequency (Hz)
0
100
200
300
400
500
600
700
800
900
1000
0
50
100
150
200
250
300
350
400

Figure D−83: Frequency Scan at Beseck 345 kV − Cont 9

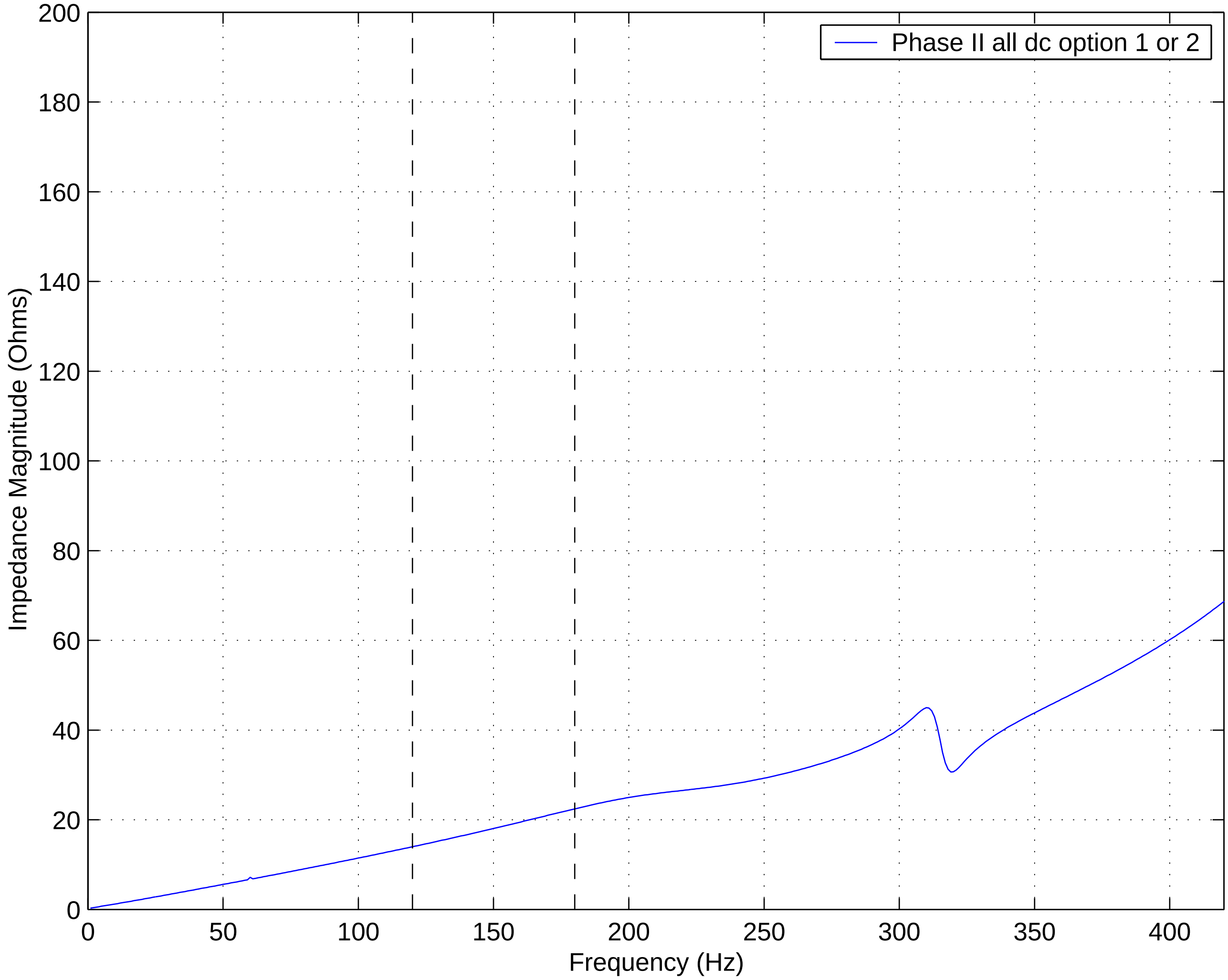
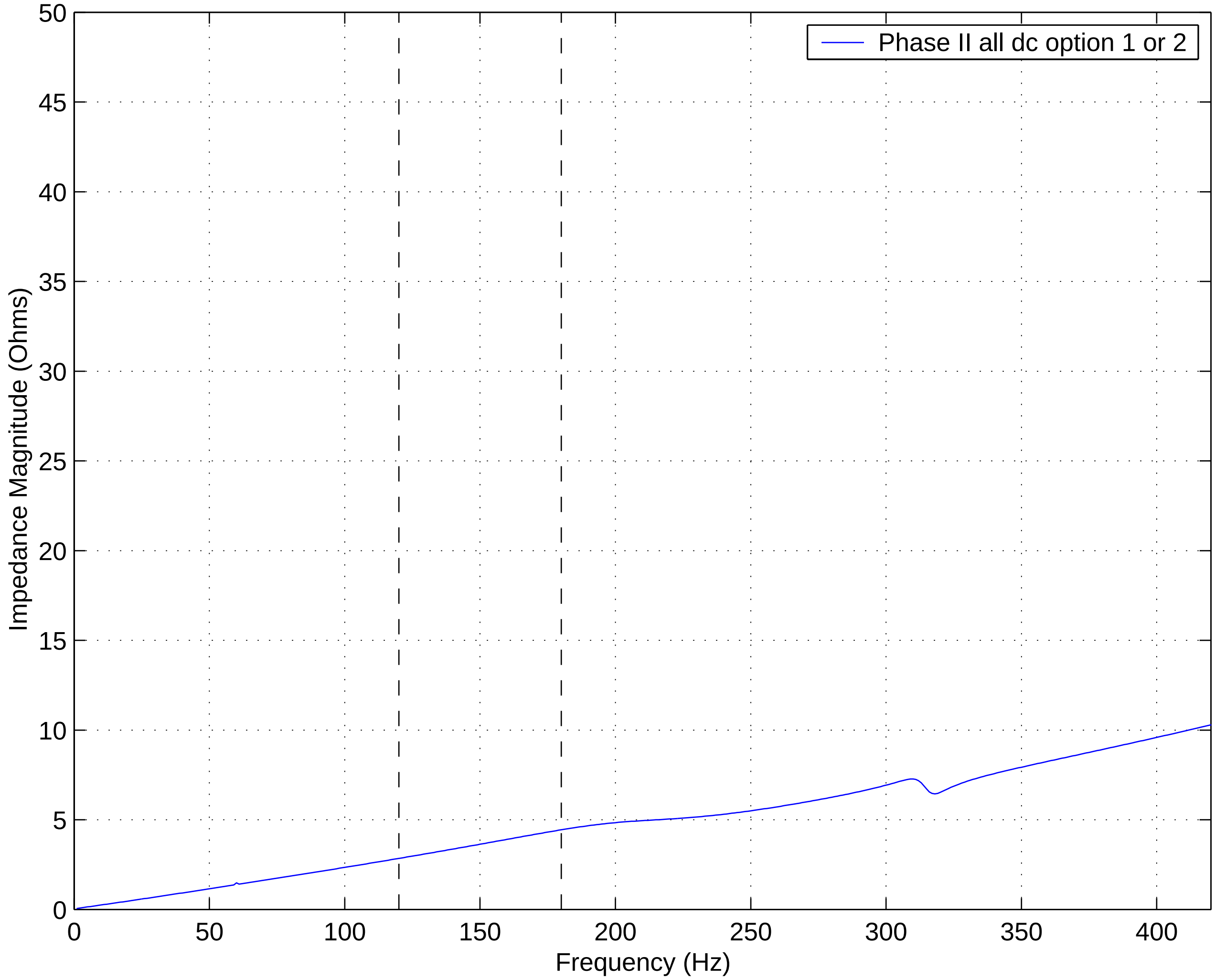


Figure D−84: Frequency Scan at Devon 115 kV − Cont 9



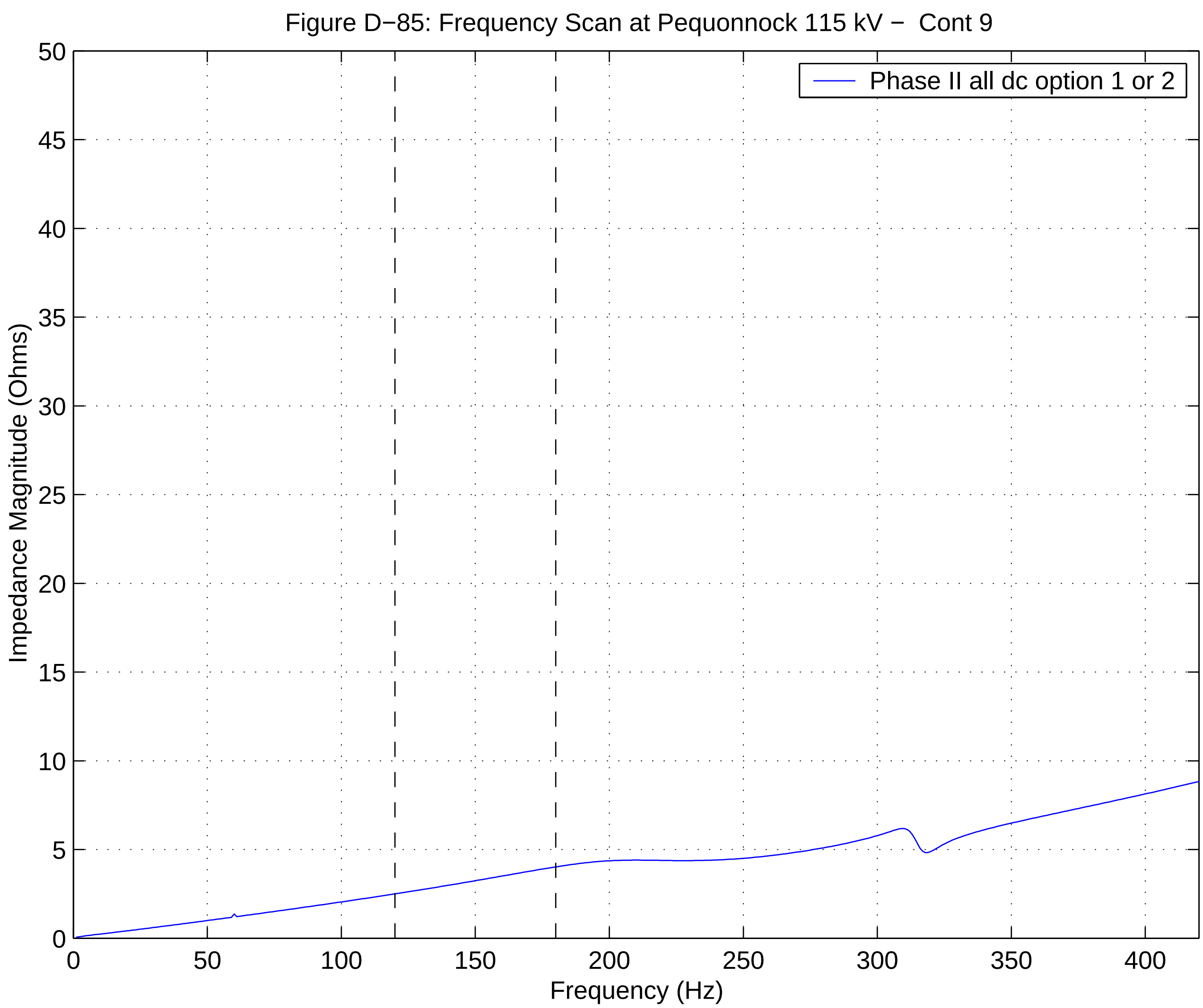
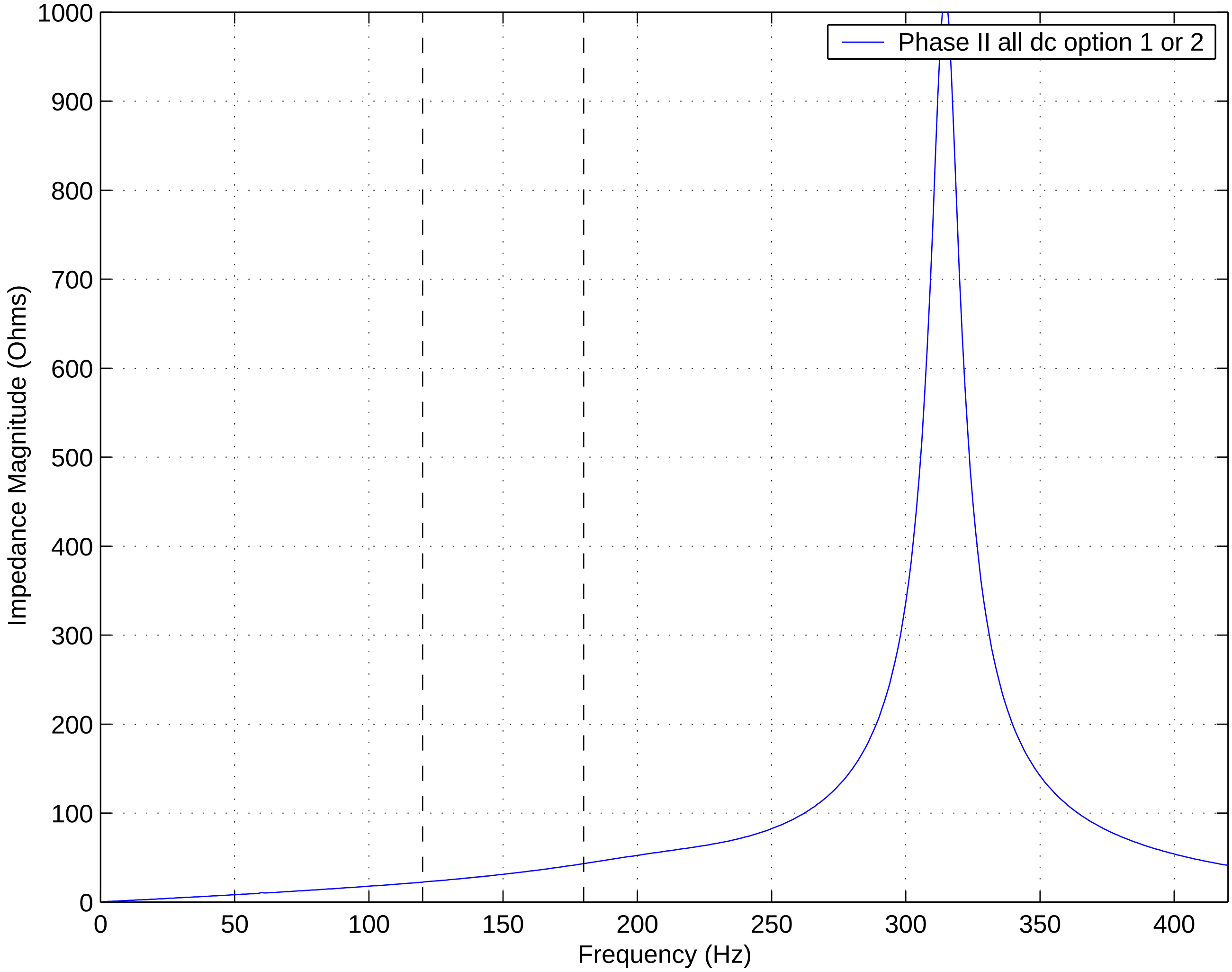


Figure D−85: Frequency Scan at Pequonnock 115 kV − Cont 9
Phase II all dc option 1 or 2
Impedance Magnitude (Ohms)
Frequency (Hz)
0
5
10
15
20
25
30
35
40
45
50
0
50
100
150
200
250
300
350
400

Figure D−86: Frequency Scan at Plumtree 345 kV − Cont 9



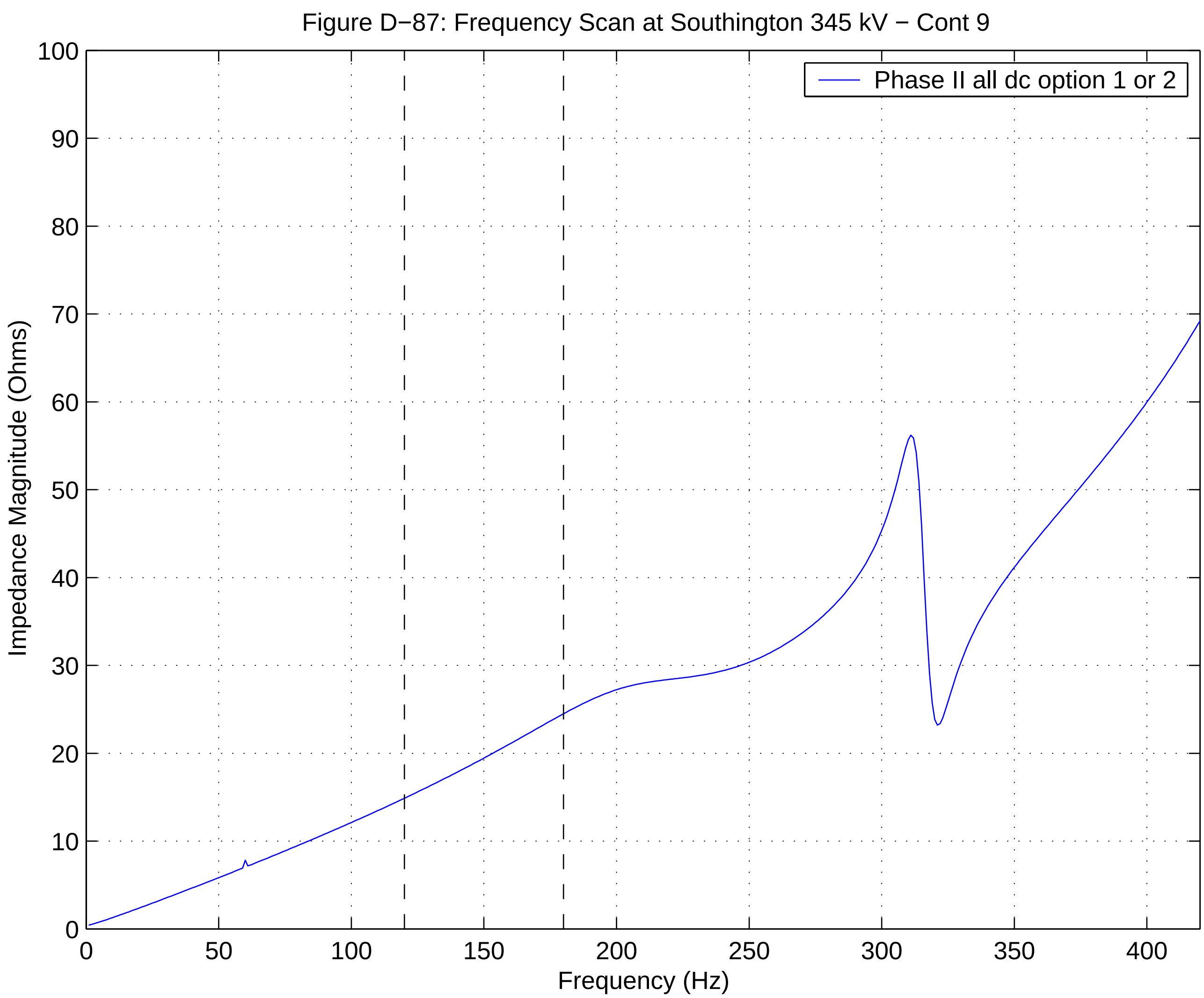


Figure D−87: Frequency Scan at Southington 345 kV − Cont 9
Phase II all dc option 1 or 2
Impedance Magnitude (Ohms)
Frequency (Hz)
0
10
20
30
40
50
60
70
80
90
100
0
50
100
150
200
250
300
350
400

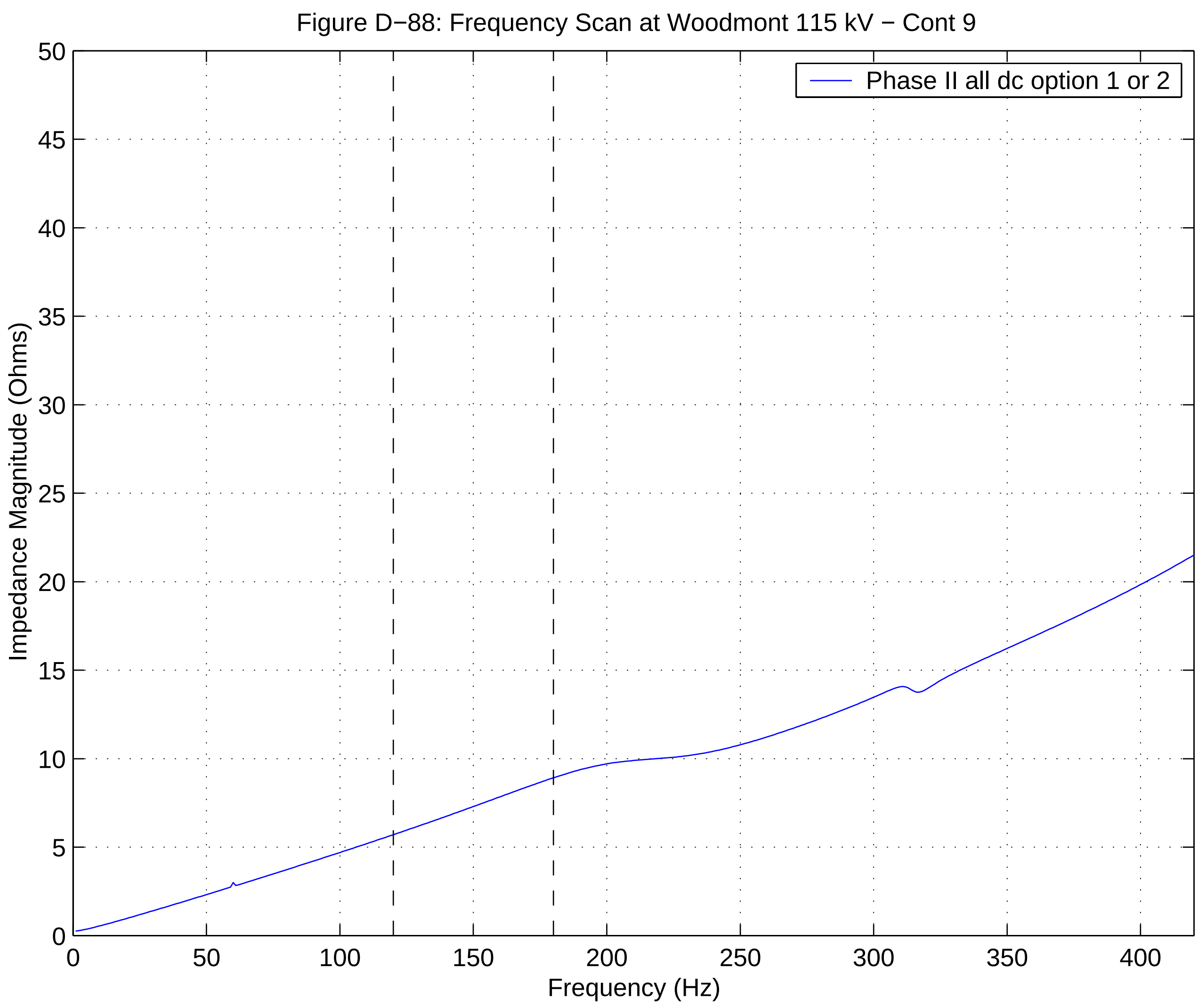
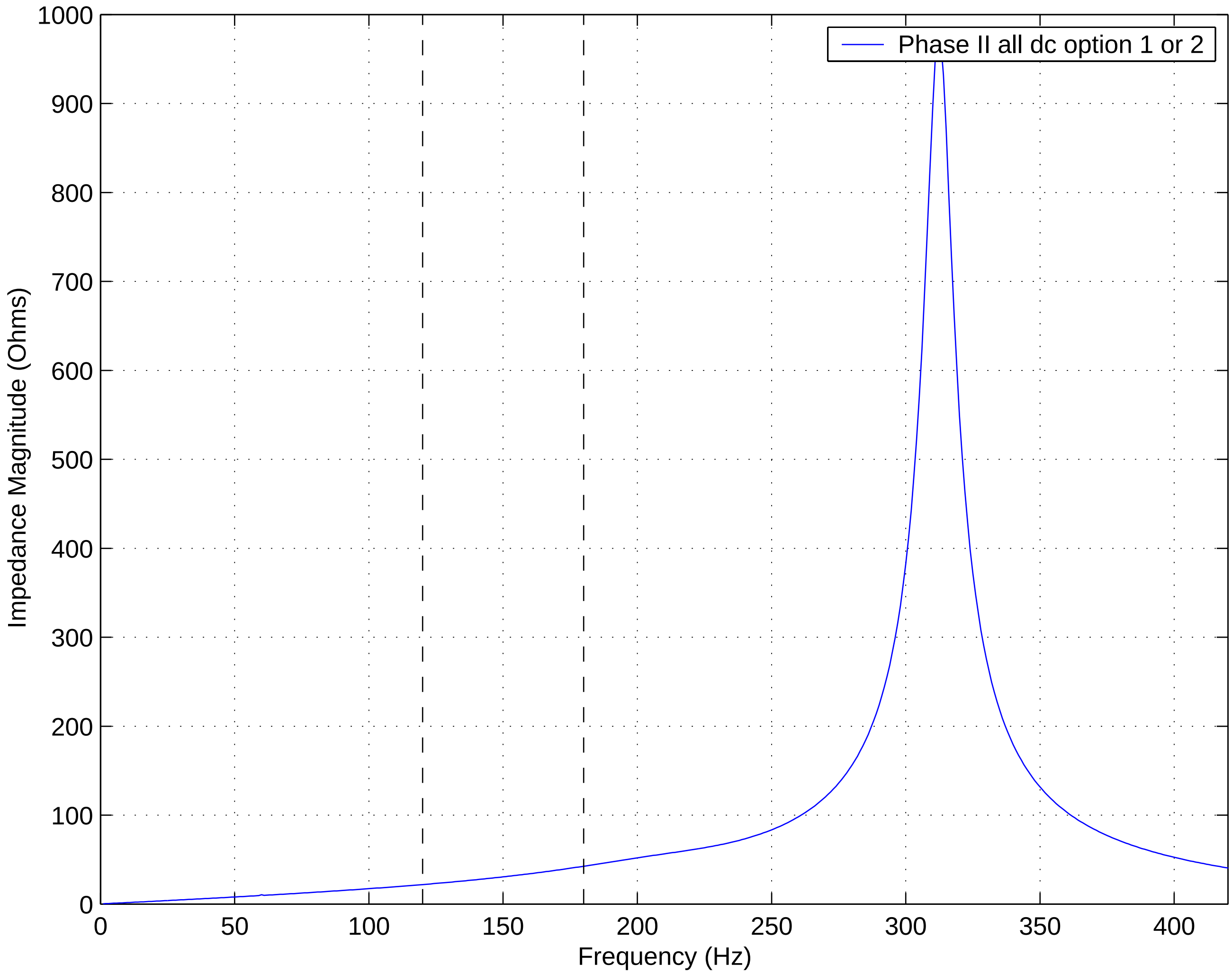


Figure D−88: Frequency Scan at Woodmont 115 kV − Cont 9
Phase II all dc option 1 or 2
Impedance Magnitude (Ohms)
Frequency (Hz)
0
5
10
15
20
25
30
35
40
45
50
0
50
100
150
200
250
300
350
400

Figure D−89: Frequency Scan at Norwalk 345 kV − Cont 10



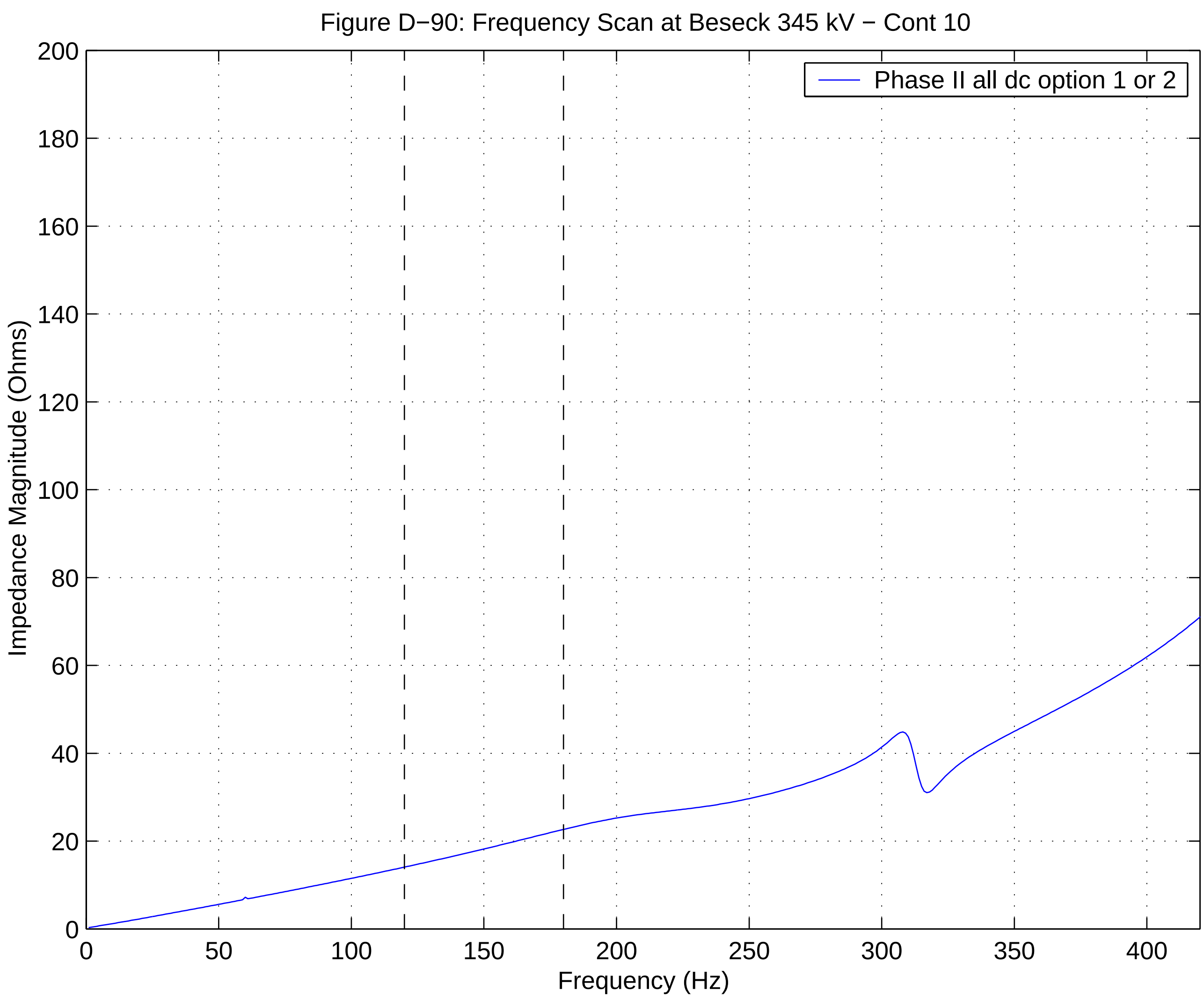


Figure D−90: Frequency Scan at Beseck 345 kV − Cont 10
Phase II all dc option 1 or 2
Impedance Magnitude (Ohms)
Frequency (Hz)
0
20
40
60
80
100
120
140
160
180
200
0
50
100
150
200
250
300
350
400

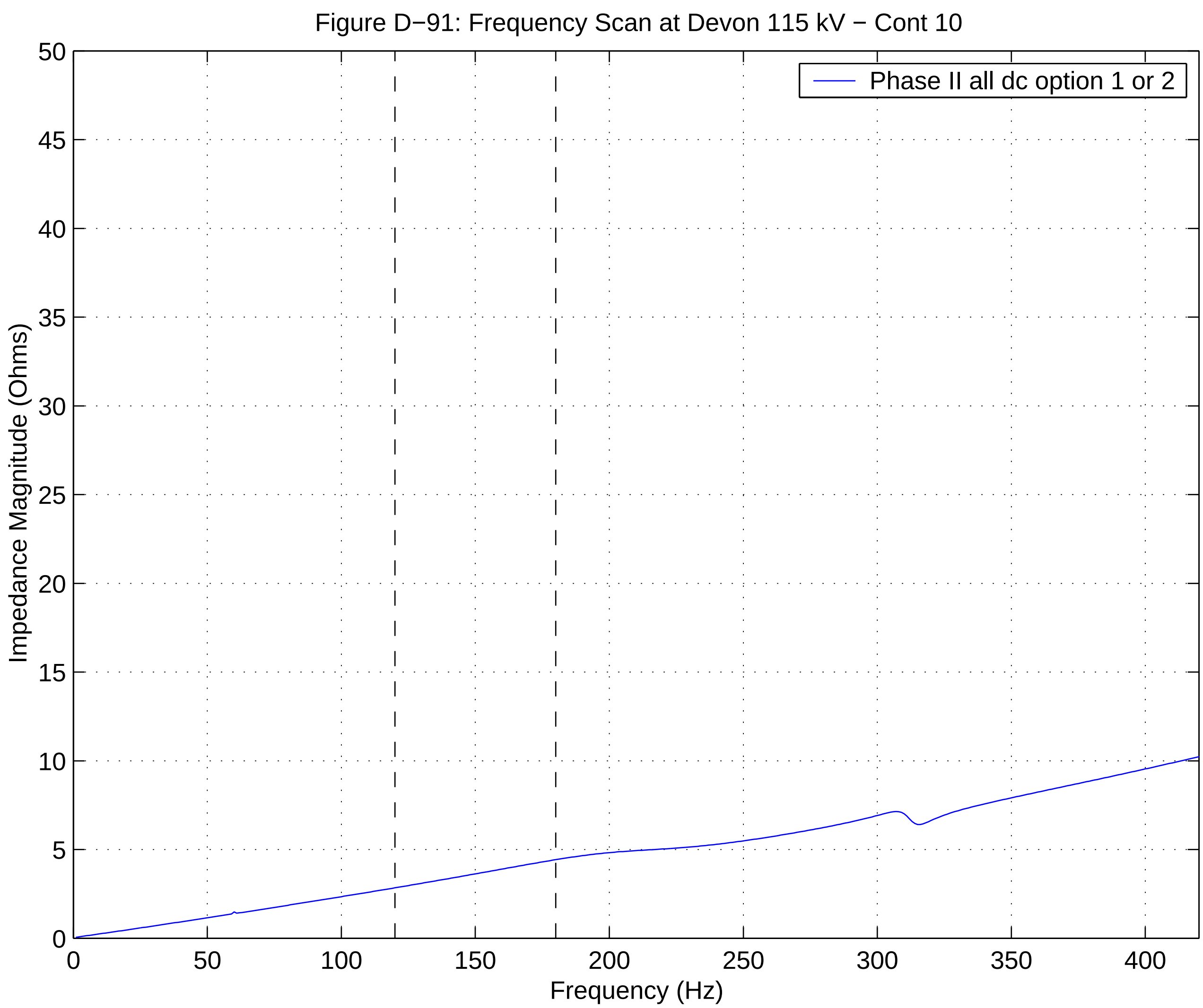


Figure D−91: Frequency Scan at Devon 115 kV − Cont 10
Phase II all dc option 1 or 2
Impedance Magnitude (Ohms)
Frequency (Hz)
0
5
10
15
20
25
30
35
40
45
50
0
50
100
150
200
250
300
350
400

Figure D−92: Frequency Scan at Pequonnock 115 kV − Cont 10

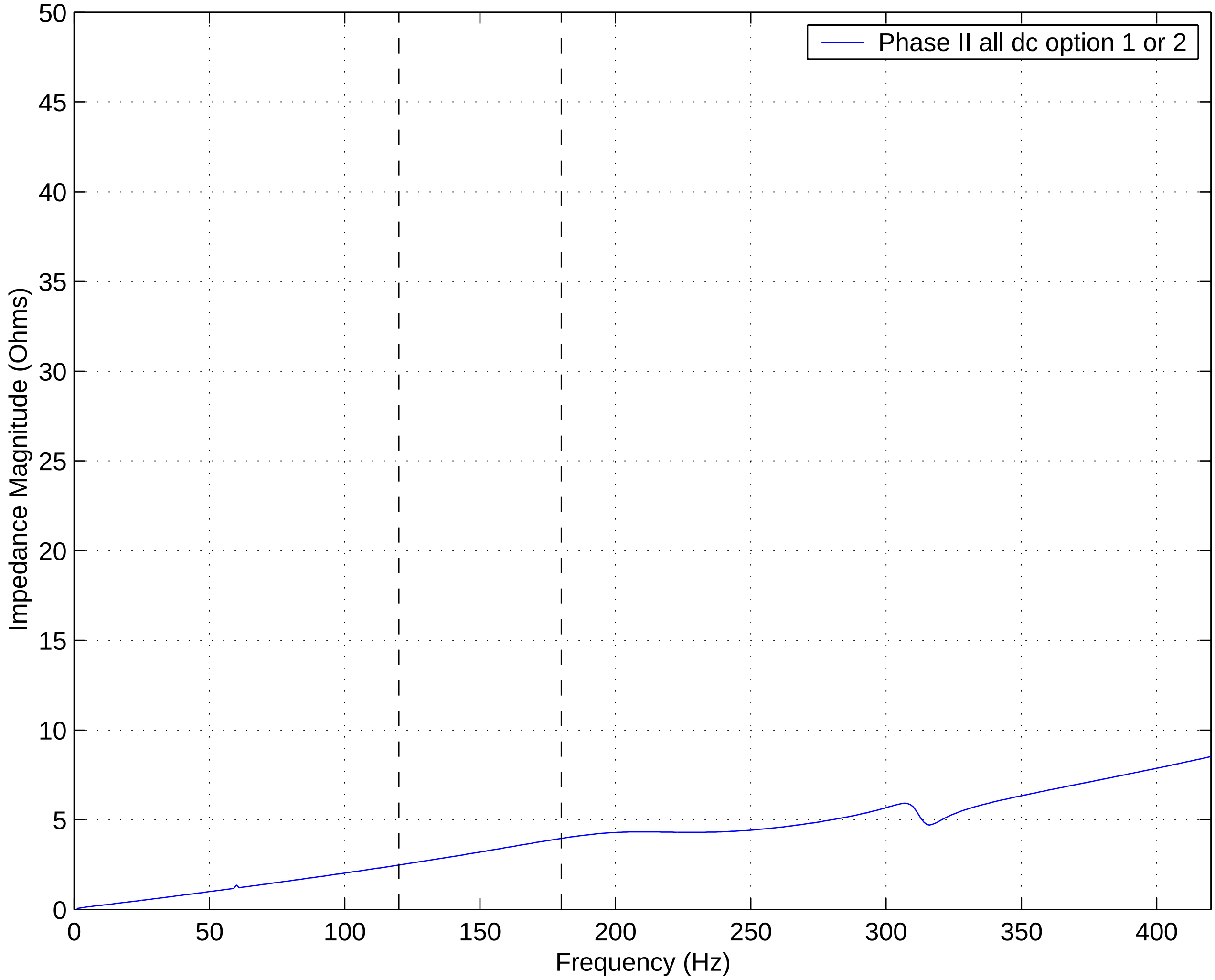
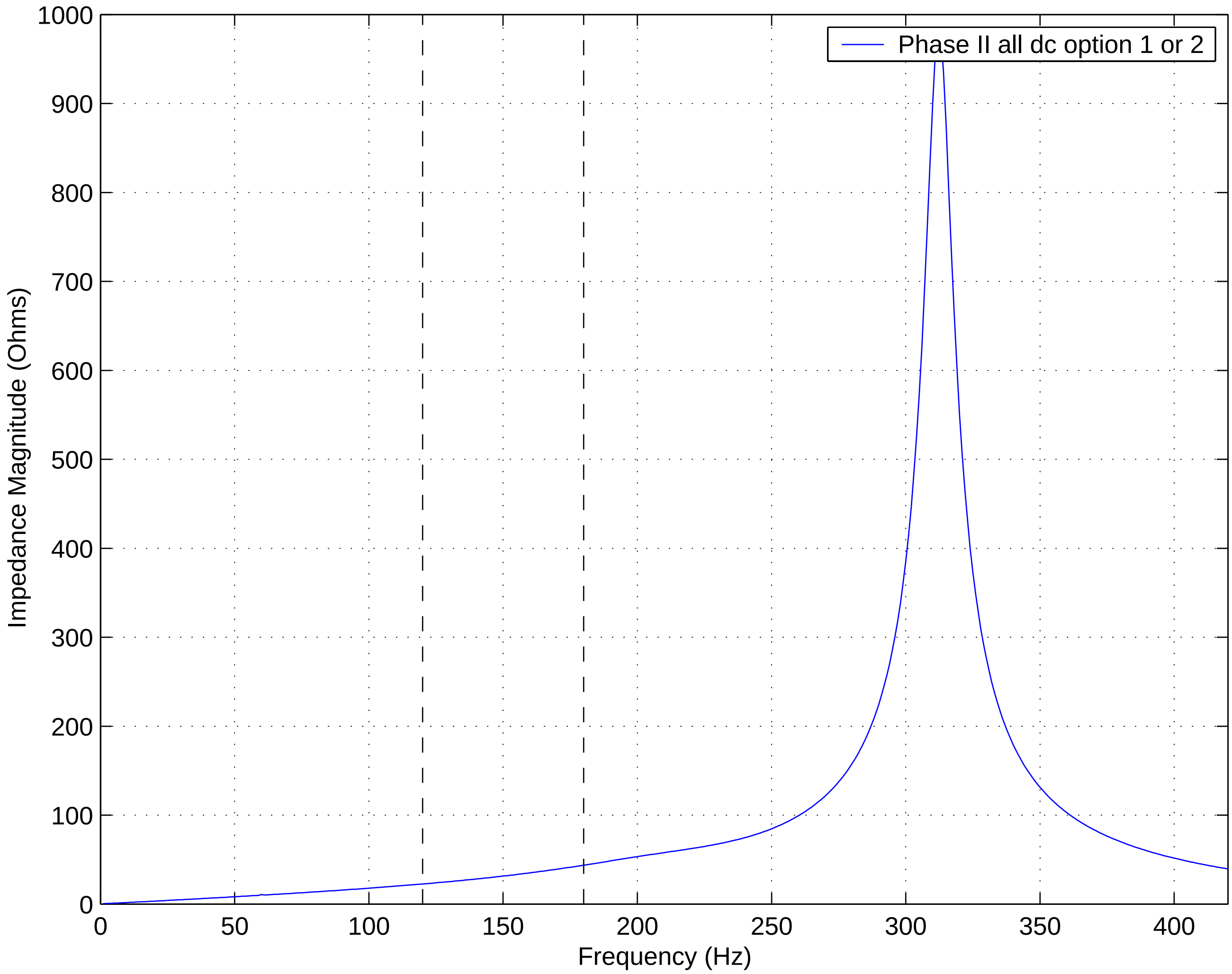


Figure D−93: Frequency Scan at Plumtree 345 kV − Cont 10



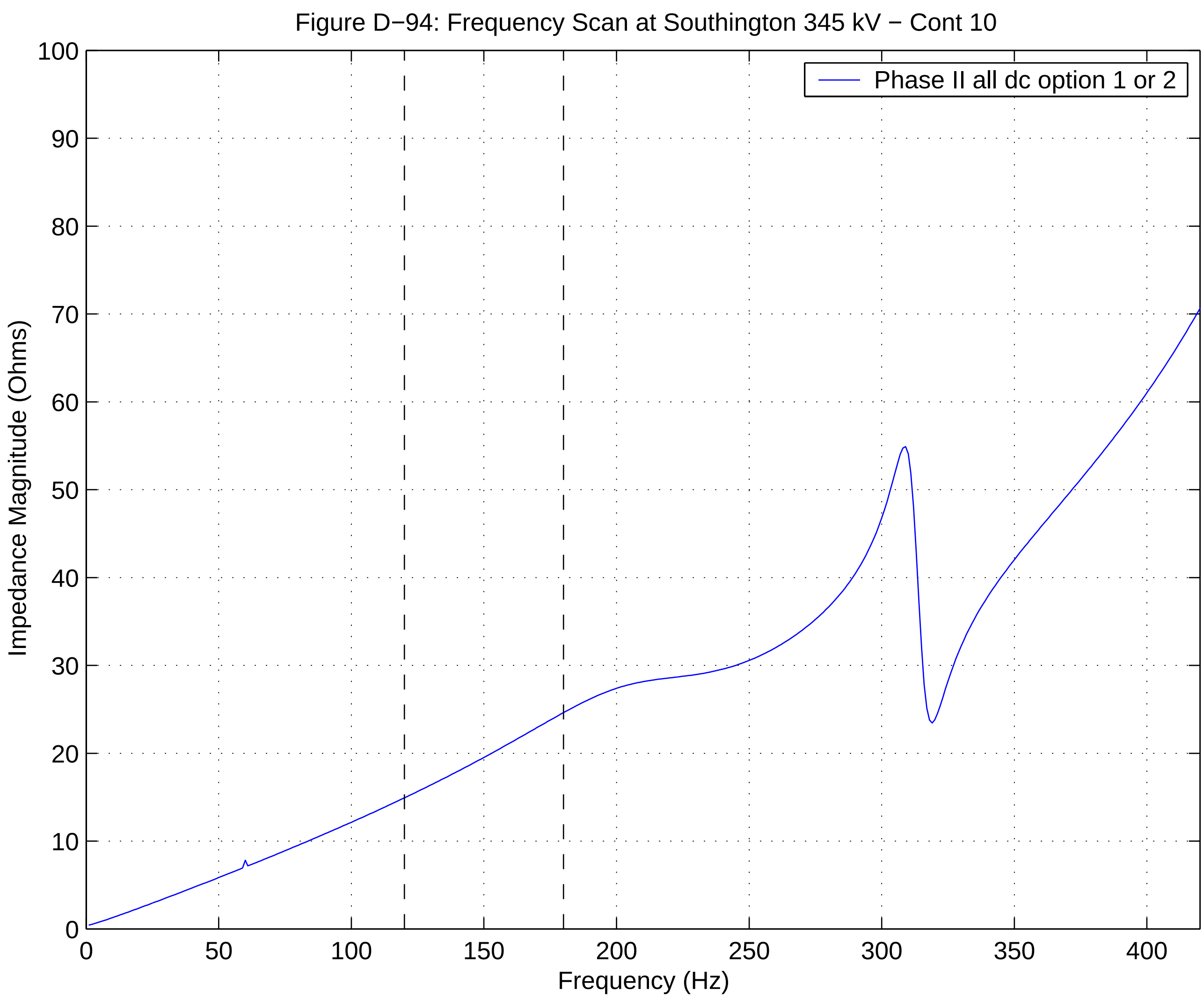


Figure D−94: Frequency Scan at Southington 345 kV − Cont 10
Phase II all dc option 1 or 2
Impedance Magnitude (Ohms)
Frequency (Hz)
0
10
20
30
40
50
60
70
80
90
100
0
50
100
150
200
250
300
350
400

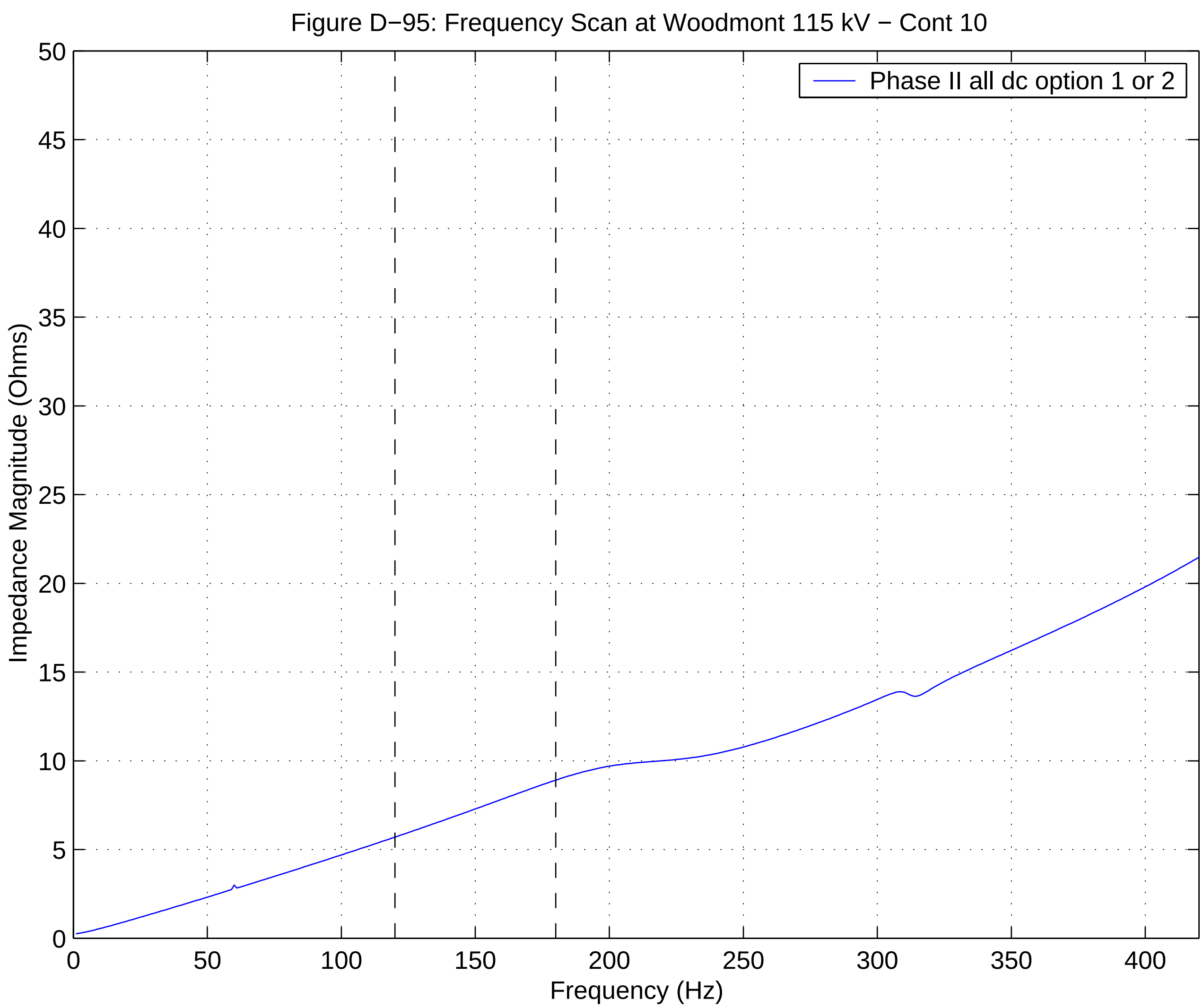


Figure D−95: Frequency Scan at Woodmont 115 kV − Cont 10
Phase II all dc option 1 or 2
Impedance Magnitude (Ohms)
Frequency (Hz)
0
5
10
15
20
25
30
35
40
45
50
0
50
100
150
200
250
300
350
400

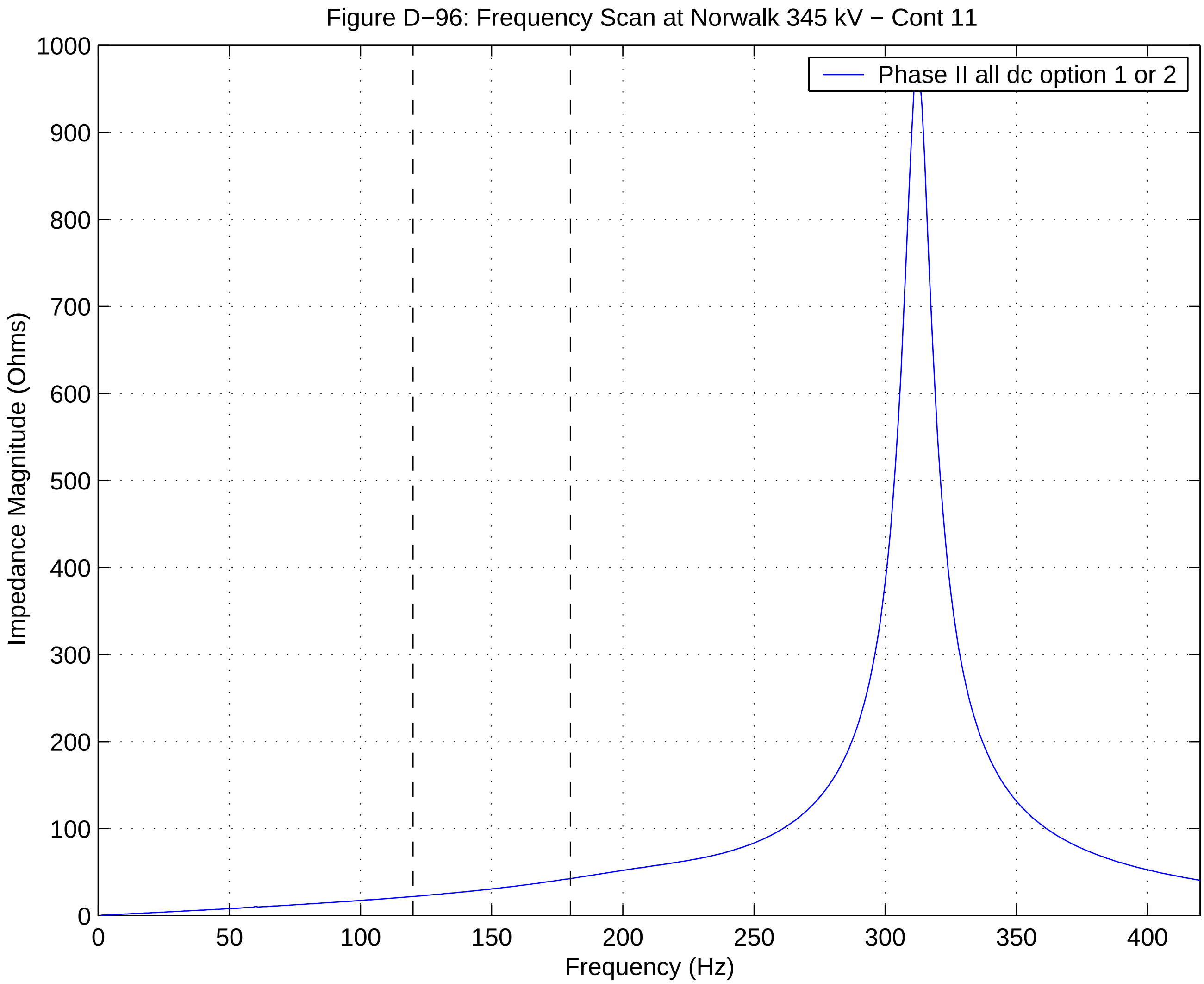
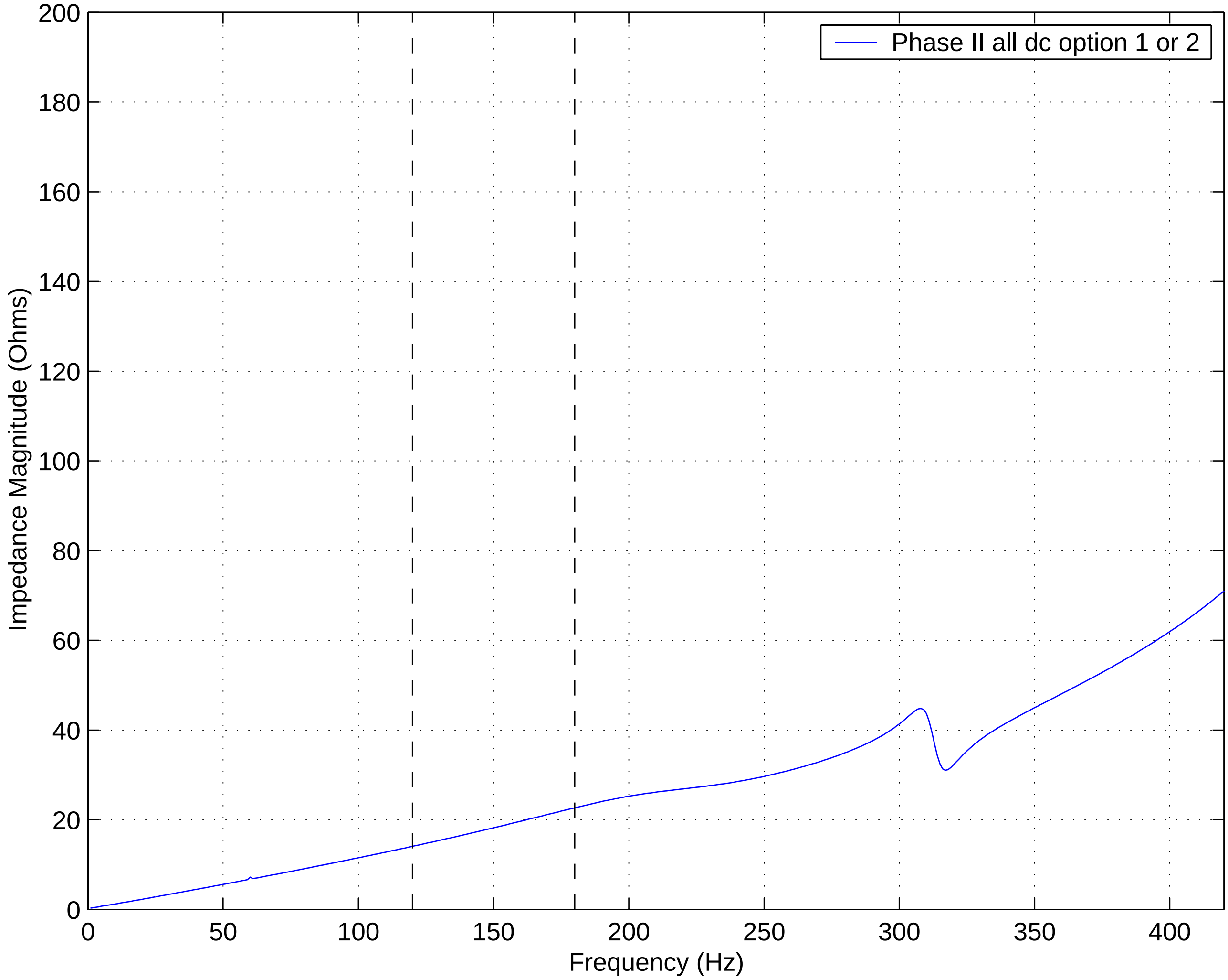


Figure D−96: Frequency Scan at Norwalk 345 kV − Cont 11
Phase II all dc option 1 or 2
Impedance Magnitude (Ohms)
Frequency (Hz)
0
100
200
300
400
500
600
700
800
900
1000
0
50
100
150
200
250
300
350
400

Figure D−97: Frequency Scan at Beseck 345 kV − Cont 11



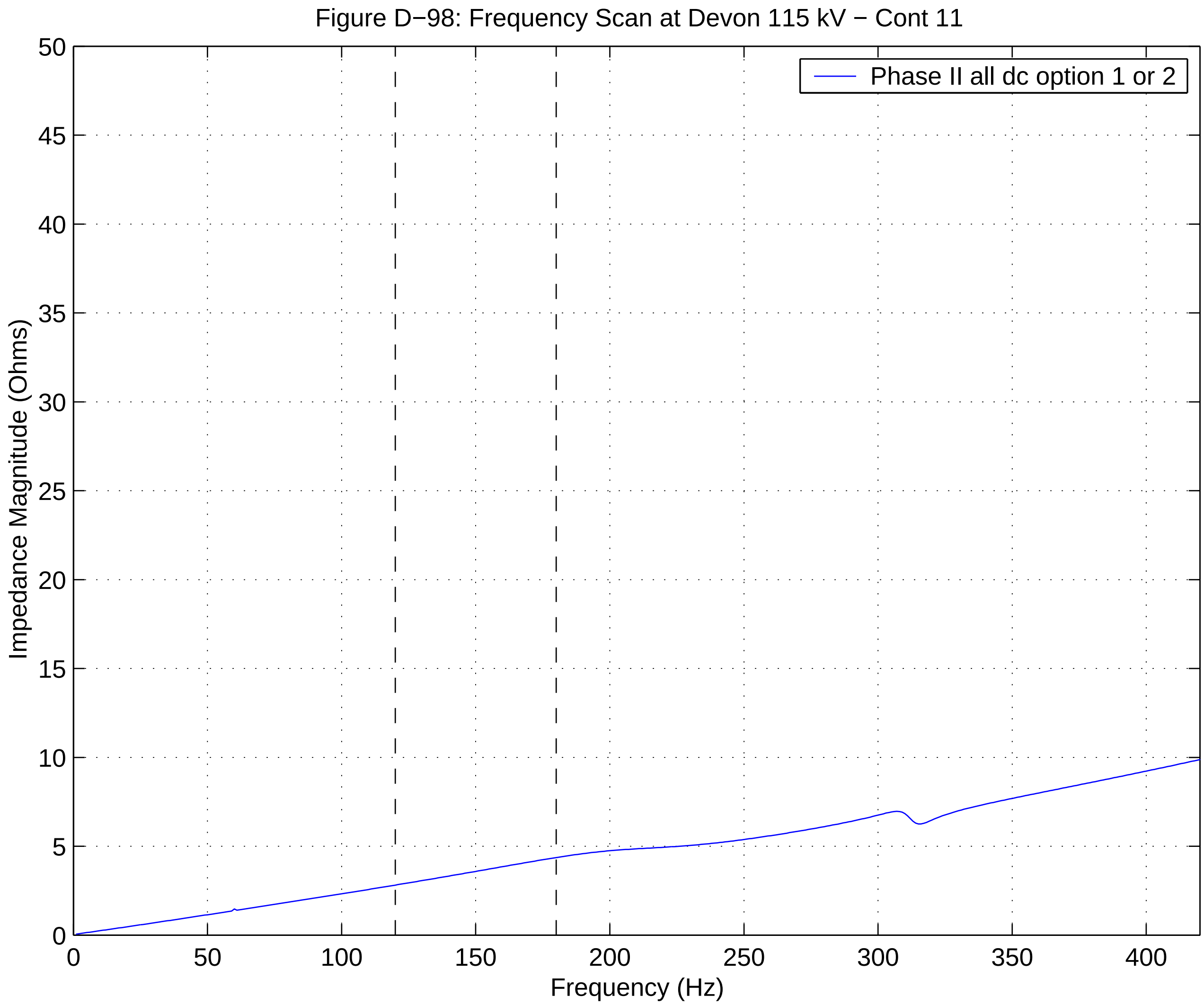


Figure D−98: Frequency Scan at Devon 115 kV − Cont 11
Phase II all dc option 1 or 2
Impedance Magnitude (Ohms)
Frequency (Hz)
0
5
10
15
20
25
30
35
40
45
50
0
50
100
150
200
250
300
350
400

Figure D−99: Frequency Scan at Pequonnock 115 kV − Cont 11

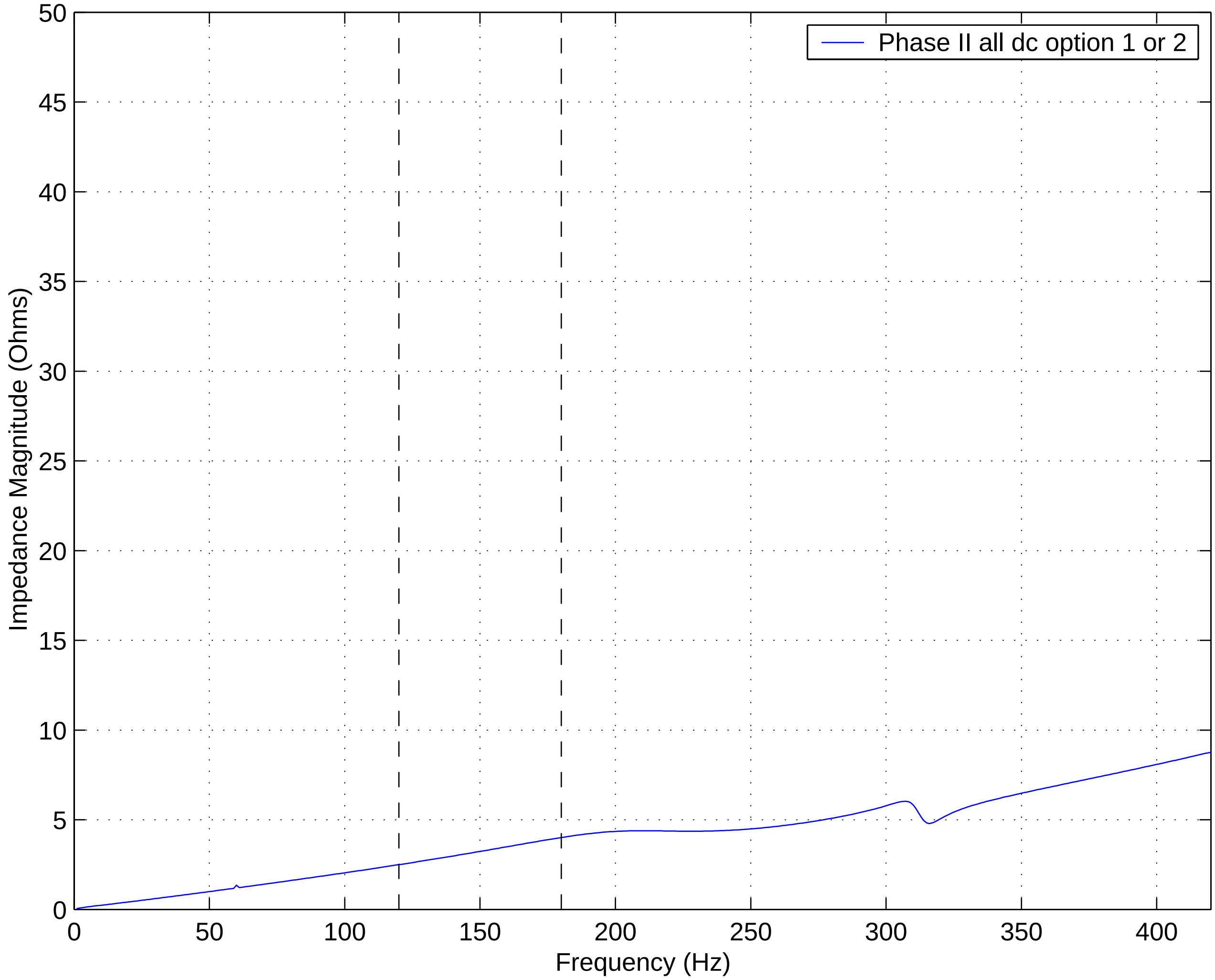
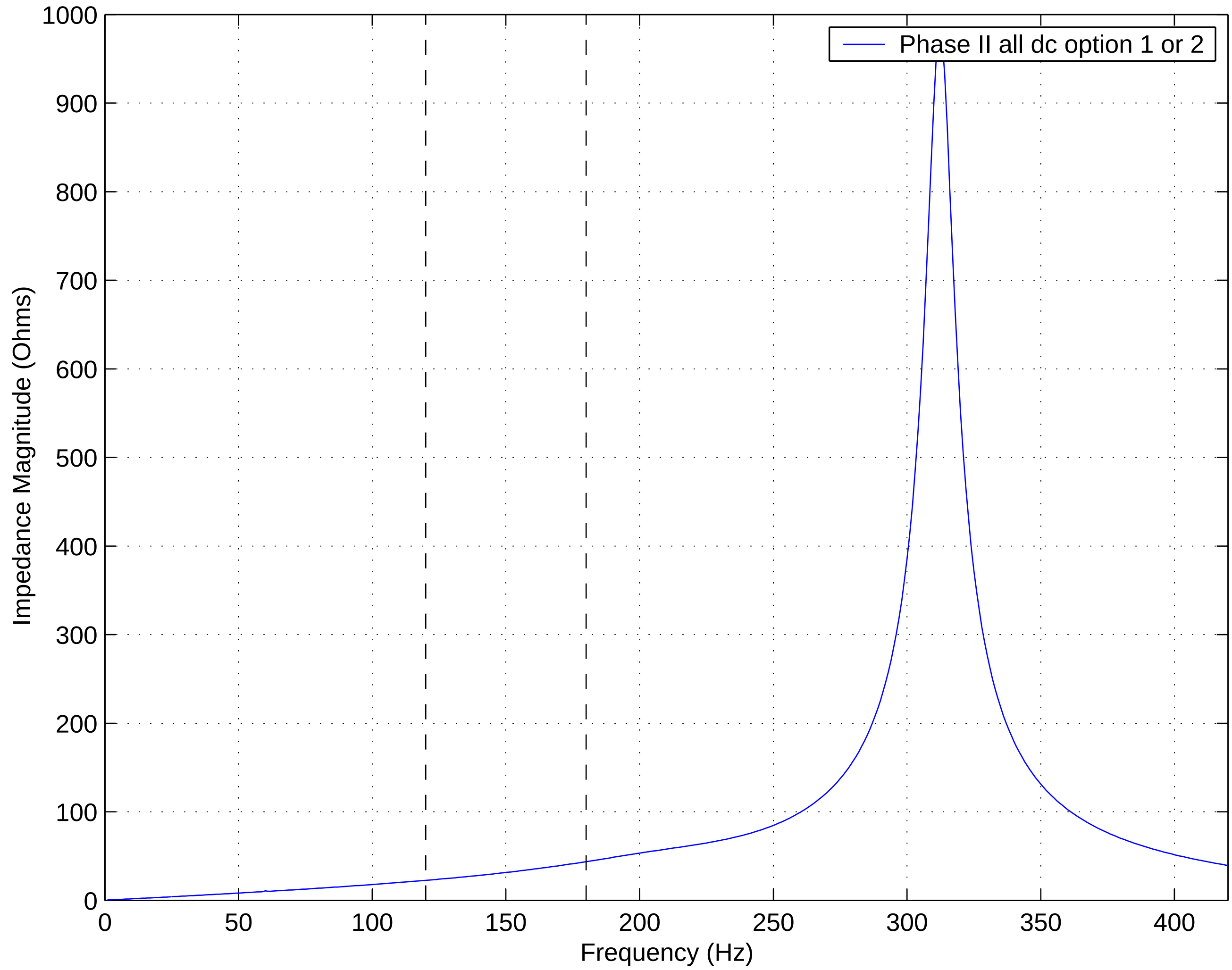


Figure D−100: Frequency Scan at Plumtree 345 kV − Cont 11



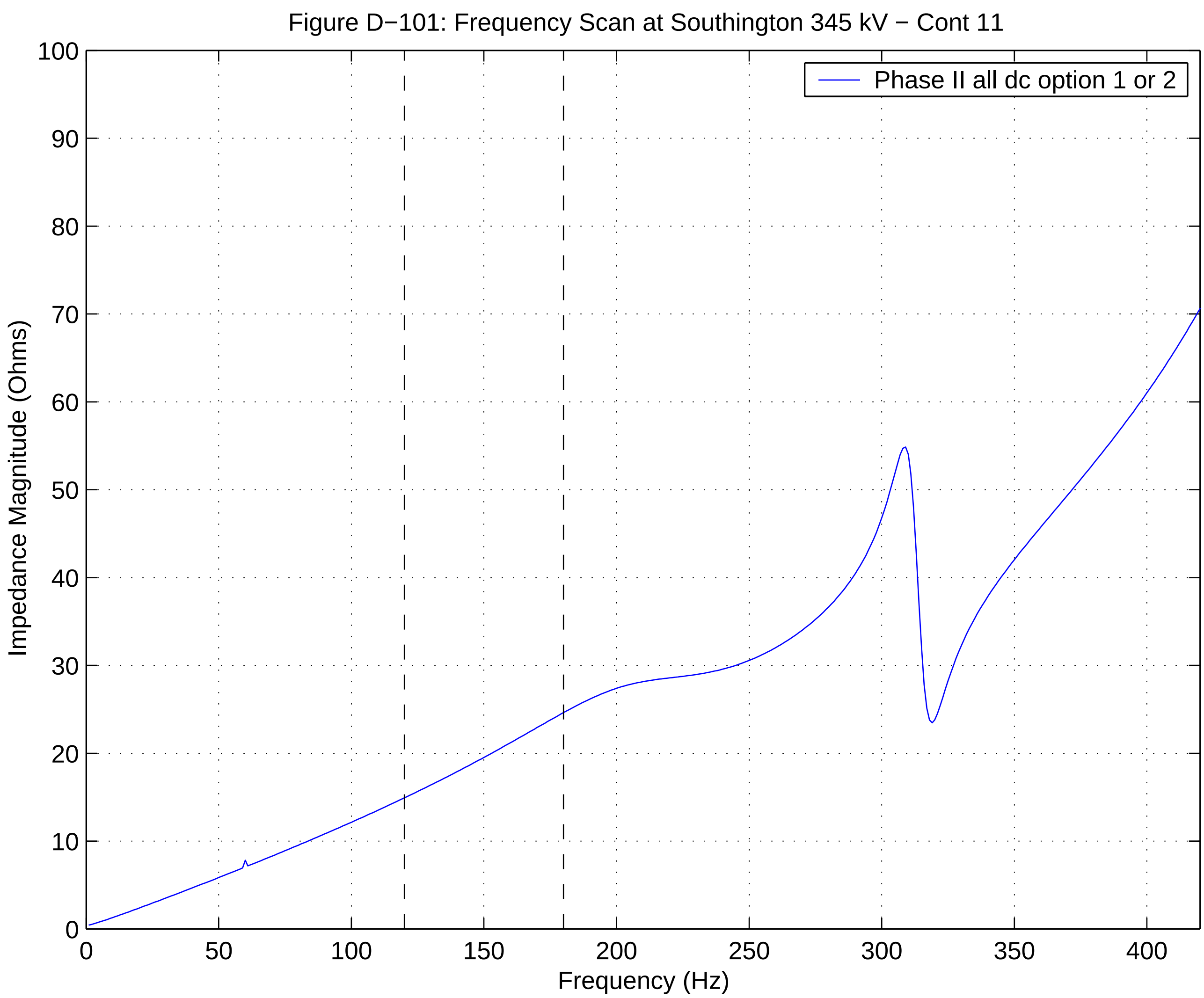


Figure D−101: Frequency Scan at Southington 345 kV − Cont 11
Phase II all dc option 1 or 2
Impedance Magnitude (Ohms)
Frequency (Hz)
0
10
20
30
40
50
60
70
80
90
100
0
50
100
150
200
250
300
350
400

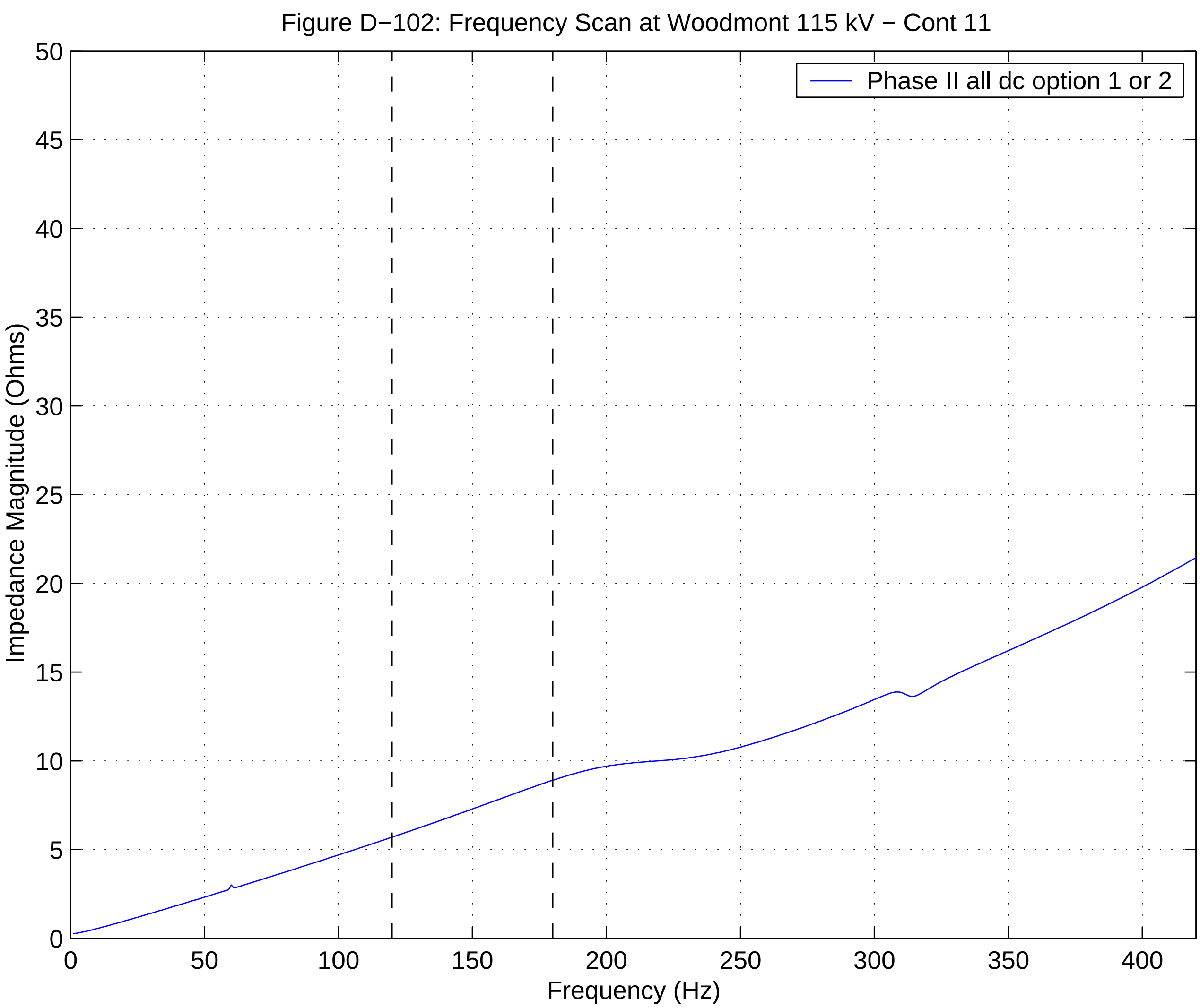


Figure D−102: Frequency Scan at Woodmont 115 kV − Cont 11
Phase II all dc option 1 or 2
Impedance Magnitude (Ohms)
Frequency (Hz)
0
5
10
15
20
25
30
35
40
45
50
0
50
100
150
200
250
300
350
400

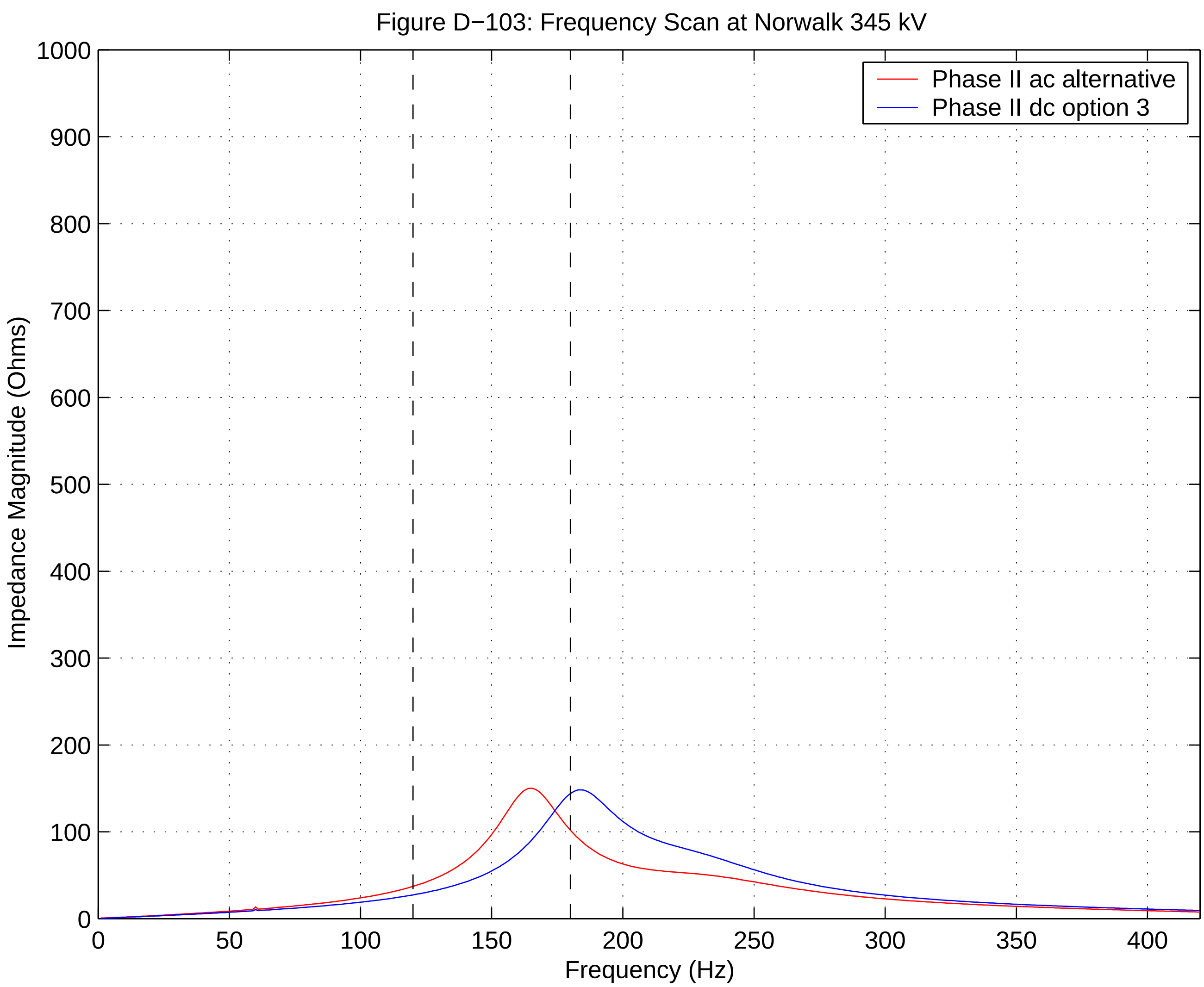


Figure D−103: Frequency Scan at Norwalk 345 kV
Phase II ac alternative
Phase II dc option 3
Impedance Magnitude (Ohms)
Frequency (Hz)
0
100
200
300
400
500
600
700
800
900
1000
0
50
100
150
200
250
300
350
400

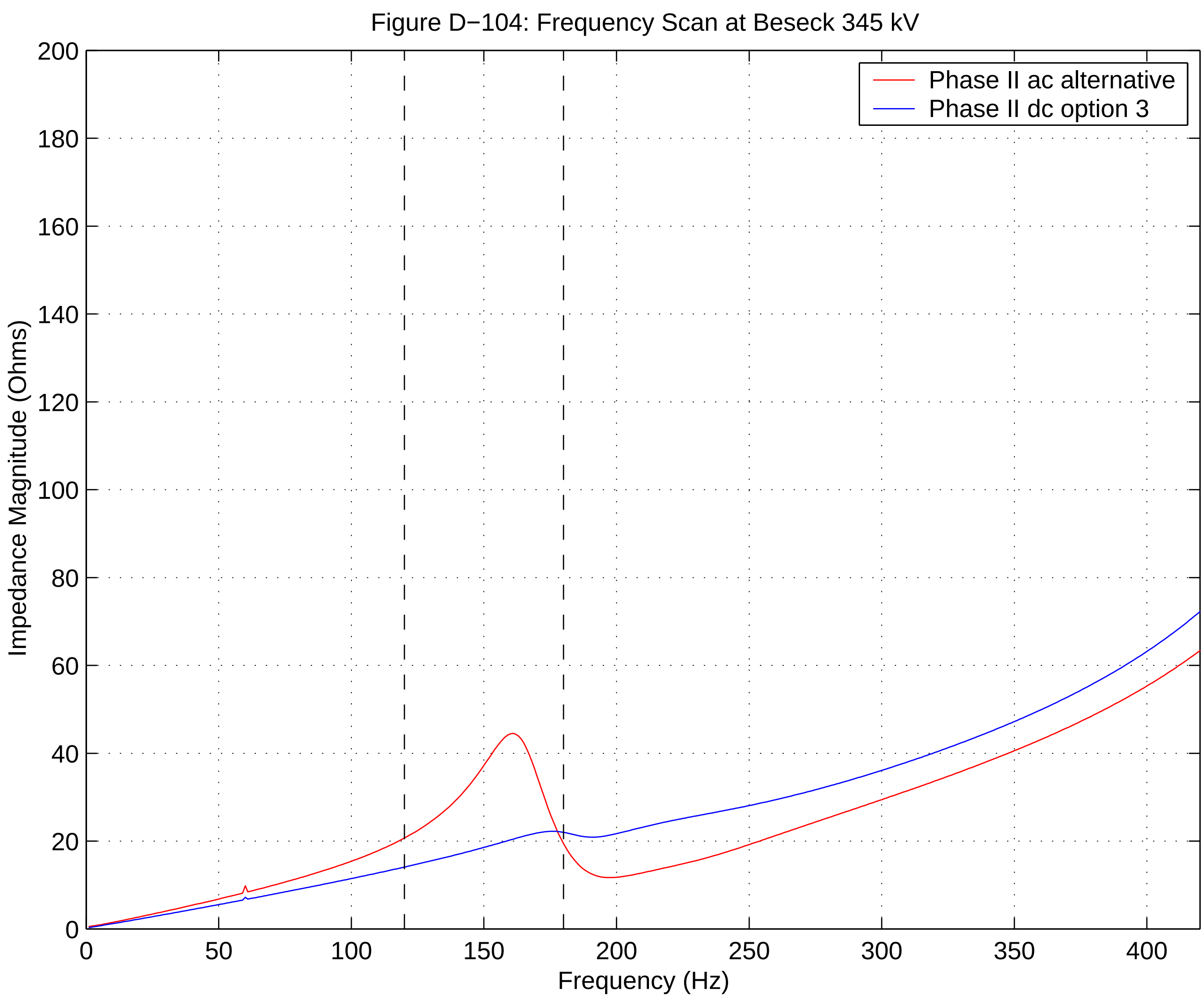


Figure D−104: Frequency Scan at Beseck 345 kV
Phase II ac alternative
Phase II dc option 3
Impedance Magnitude (Ohms)
Frequency (Hz)
0
20
40
60
80
100
120
140
160
180
200
0
50
100
150
200
250
300
350
400

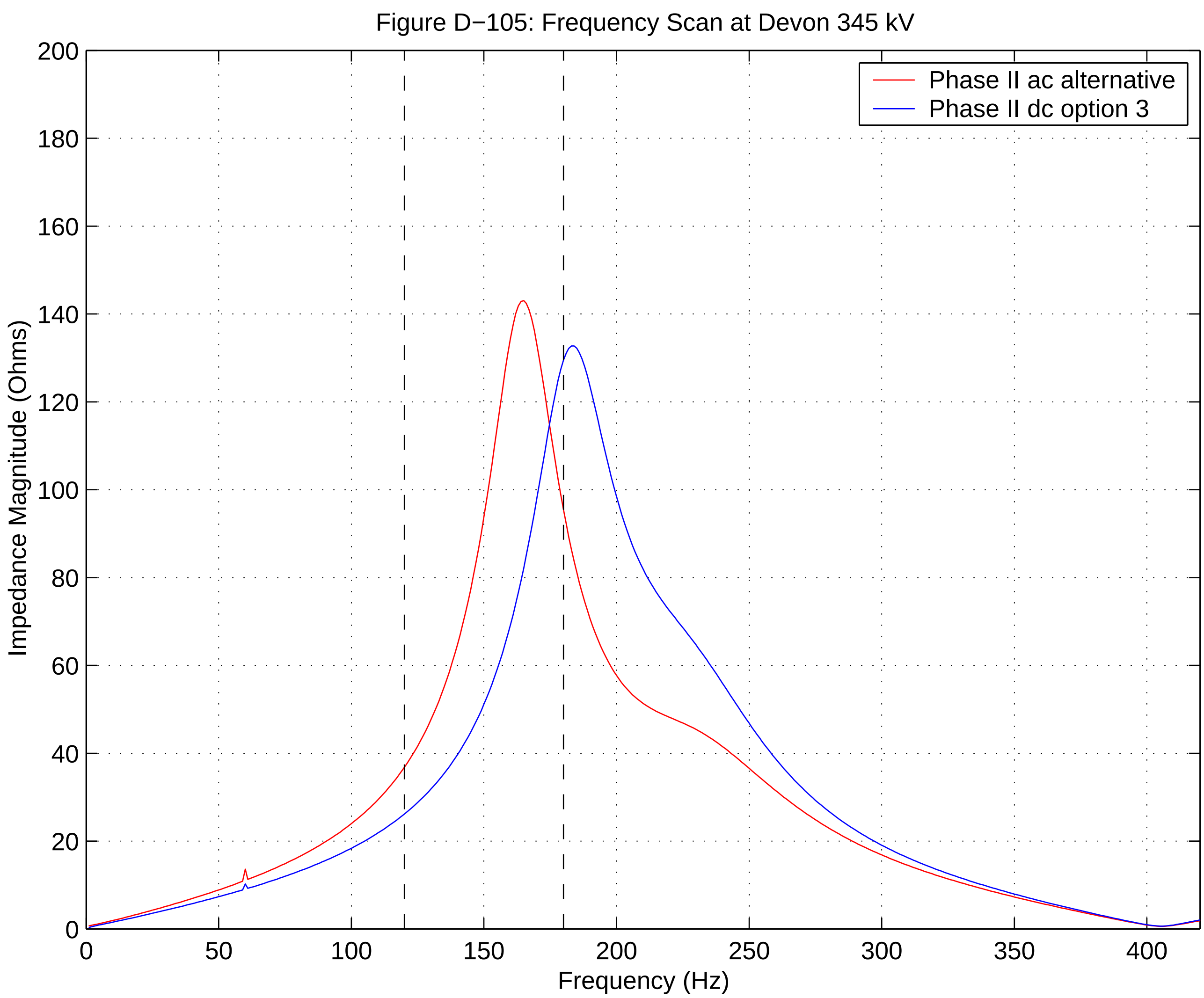
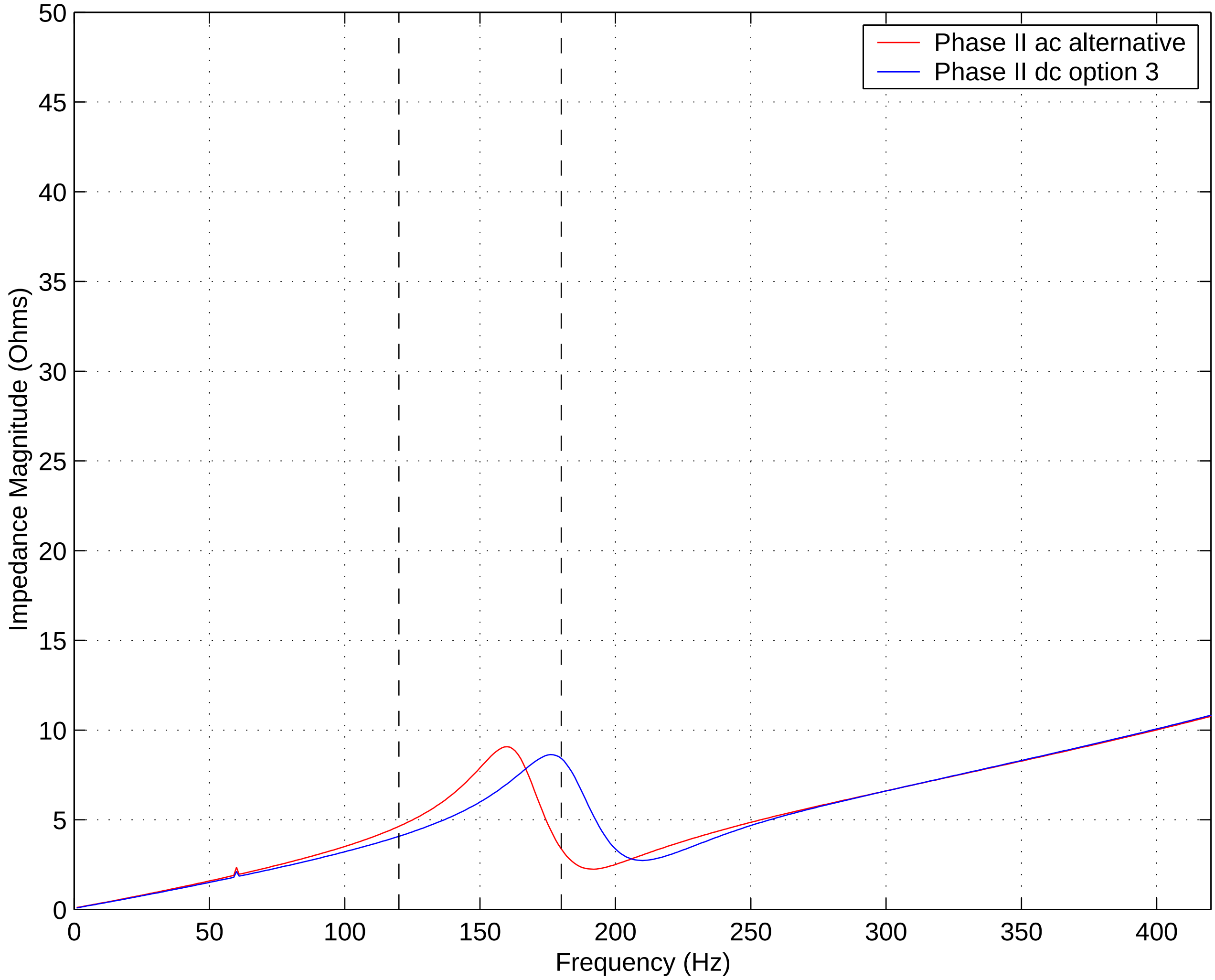


Figure D−105: Frequency Scan at Devon 345 kV
Phase II ac alternative
Phase II dc option 3
Impedance Magnitude (Ohms)
Frequency (Hz)
0
20
40
60
80
100
120
140
160
180
200
0
50
100
150
200
250
300
350
400

Figure D−106: Frequency Scan at Devon 115 kV



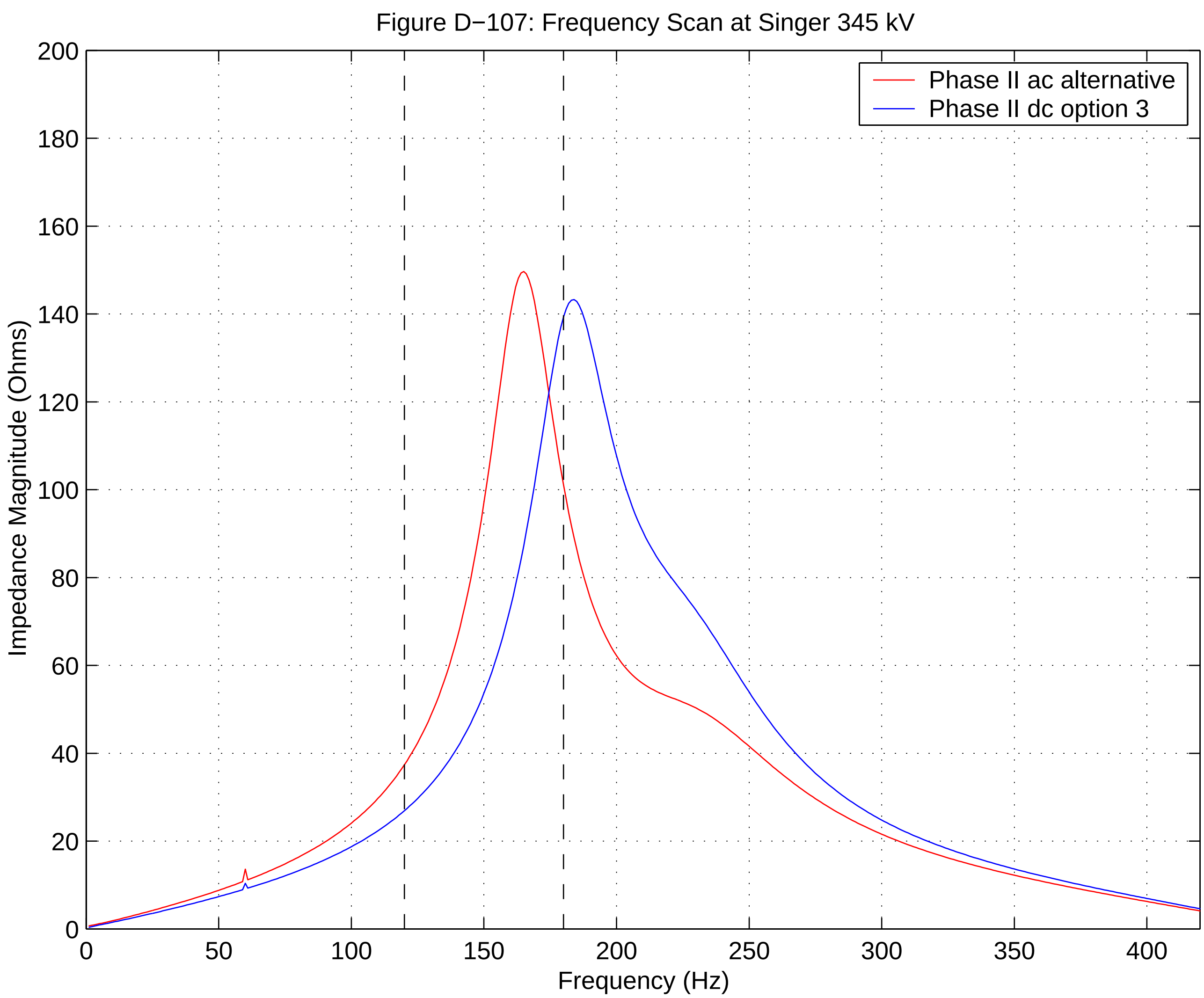


Figure D−107: Frequency Scan at Singer 345 kV
Phase II ac alternative
Phase II dc option 3
Impedance Magnitude (Ohms)
Frequency (Hz)
0
20
40
60
80
100
120
140
160
180
200
0
50
100
150
200
250
300
350
400

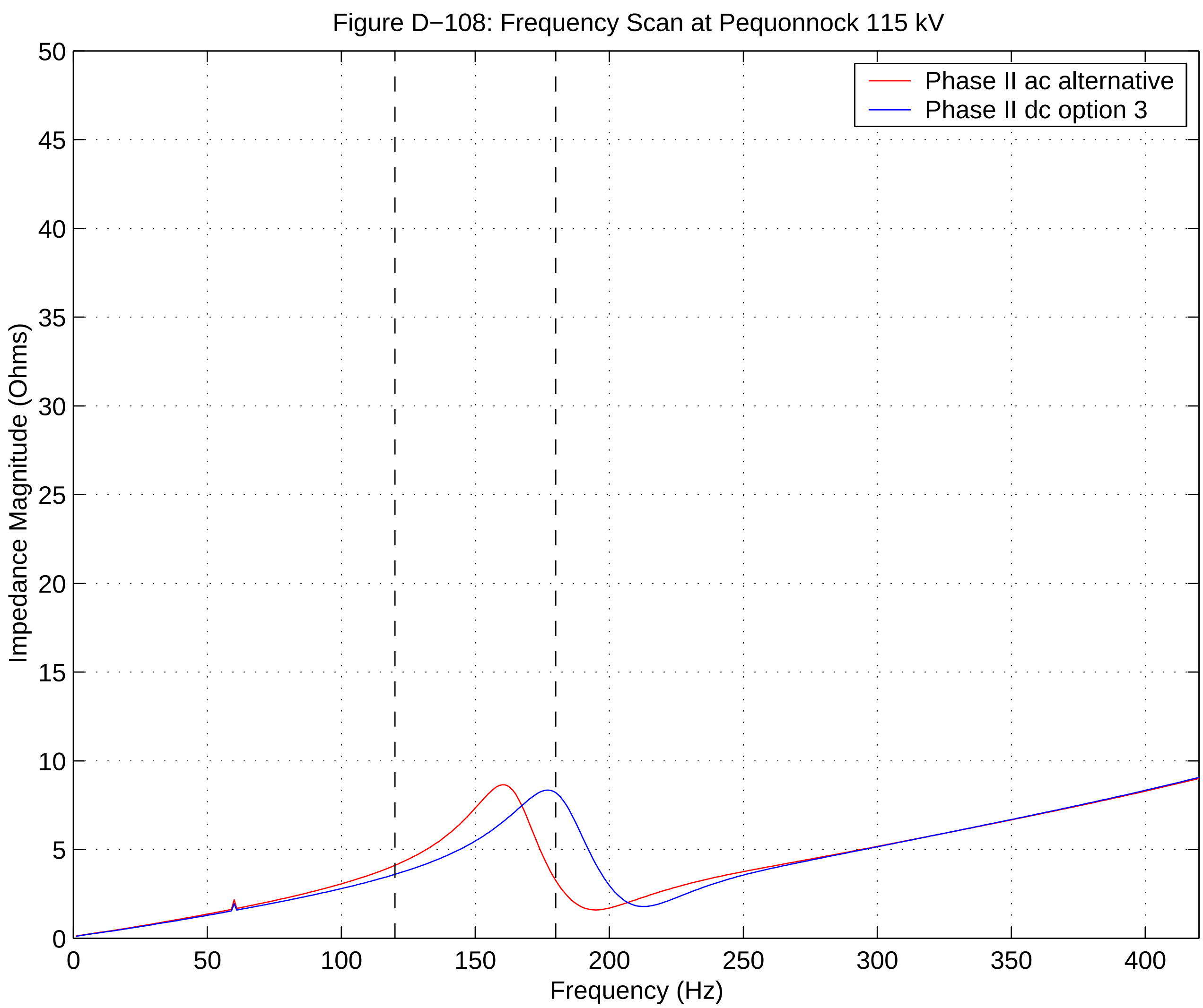
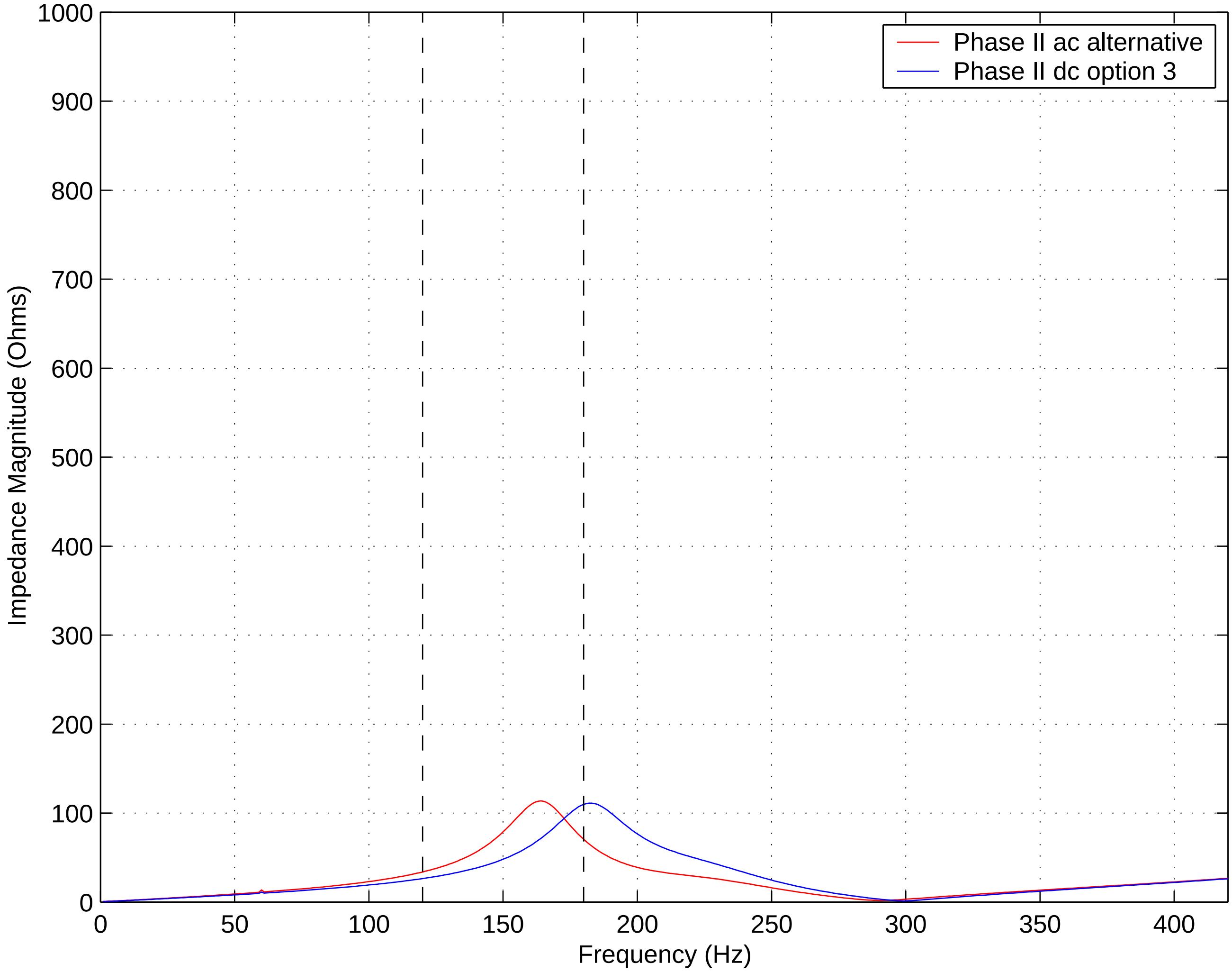


Figure D−108: Frequency Scan at Pequonnock 115 kV
Phase II ac alternative
Phase II dc option 3
Impedance Magnitude (Ohms)
Frequency (Hz)
0
5
10
15
20
25
30
35
40
45
50
0
50
100
150
200
250
300
350
400

Figure D−109: Frequency Scan at Plumtree 345 kV



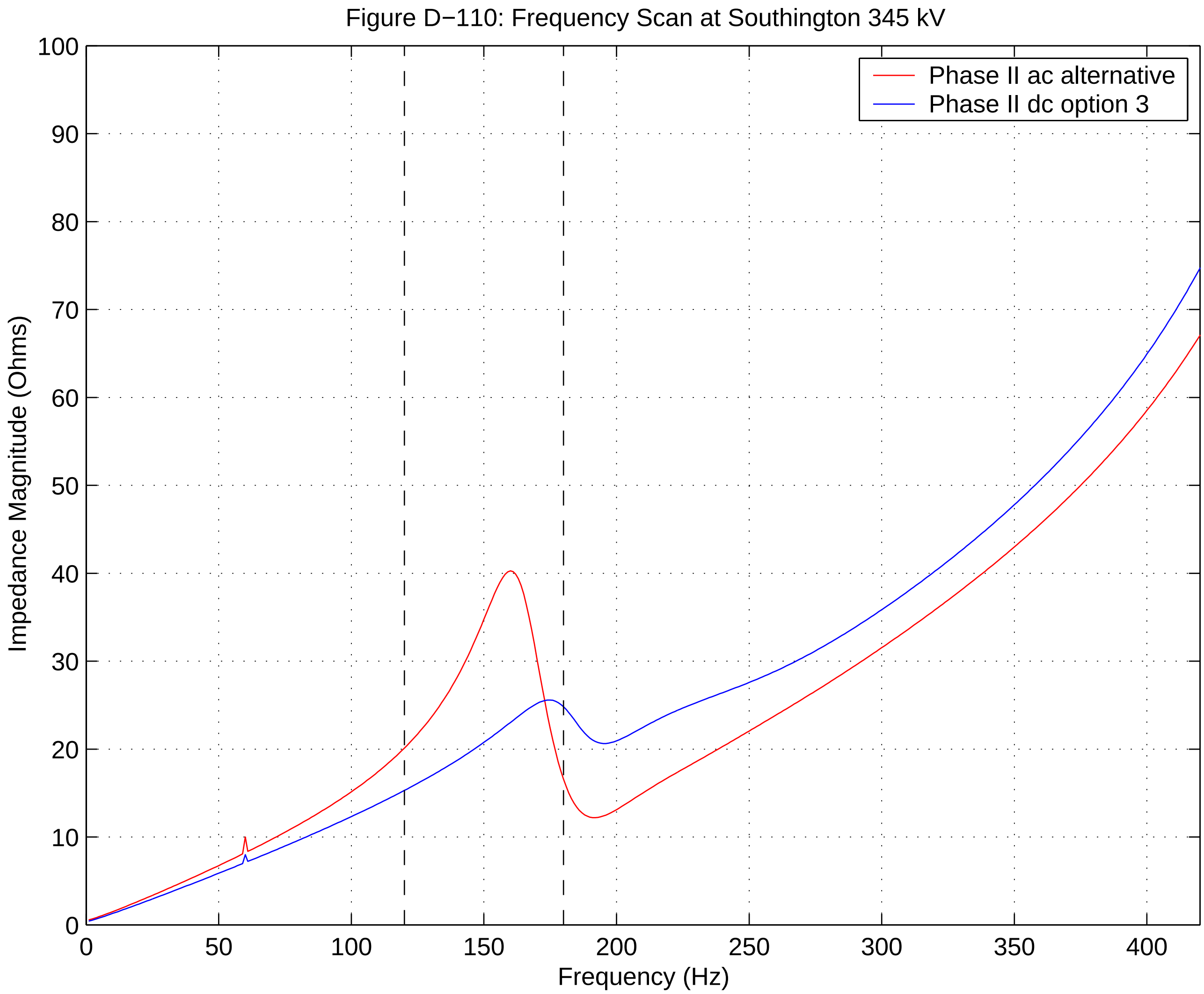


Figure D−110: Frequency Scan at Southington 345 kV
Phase II ac alternative
Phase II dc option 3
Impedance Magnitude (Ohms)
Frequency (Hz)
0
10
20
30
40
50
60
70
80
90
100
0
50
100
150
200
250
300
350
400

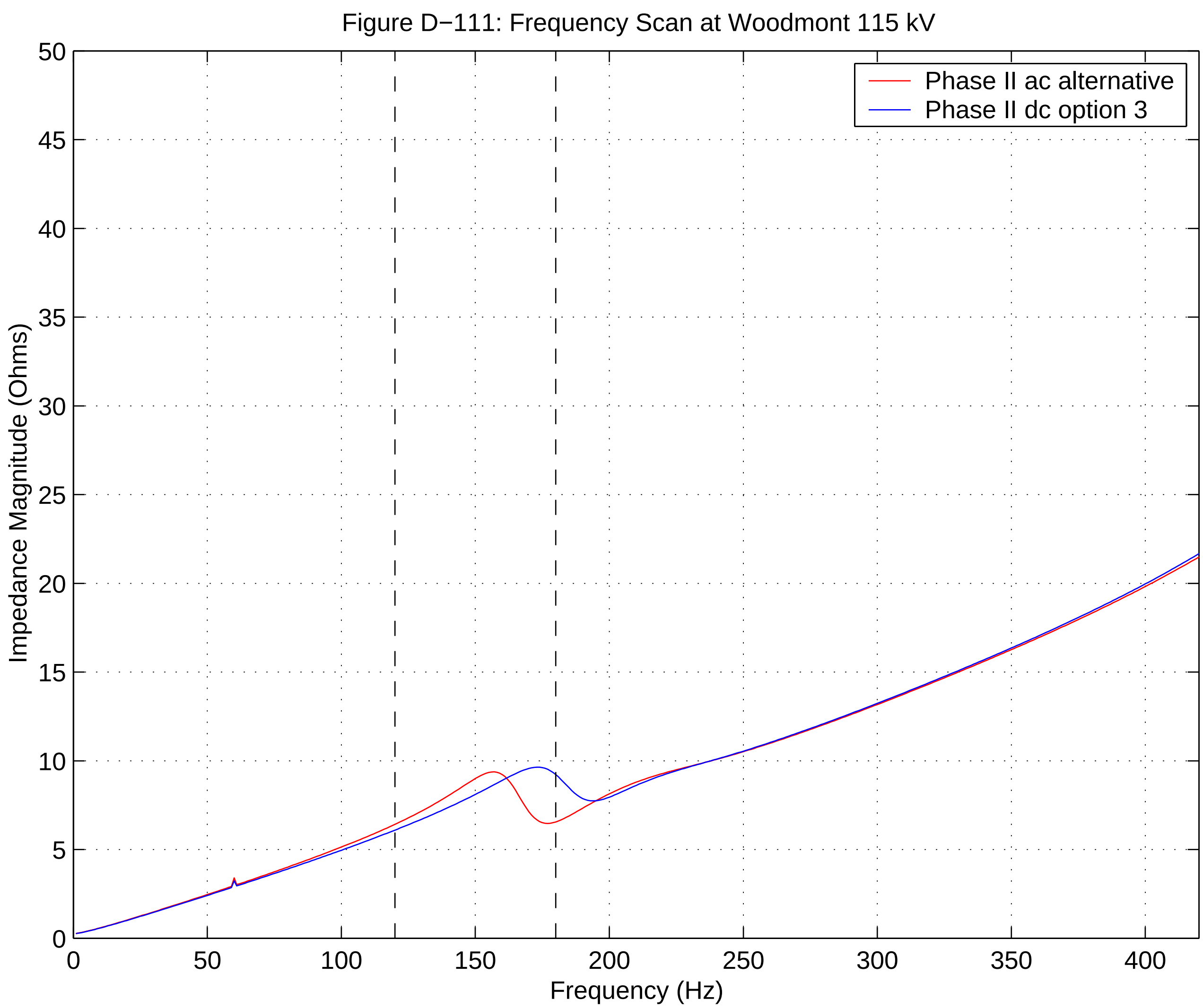


Figure D−111: Frequency Scan at Woodmont 115 kV
Phase II ac alternative
Phase II dc option 3
Impedance Magnitude (Ohms)
Frequency (Hz)
0
5
10
15
20
25
30
35
40
45
50
0
50
100
150
200
250
300
350
400

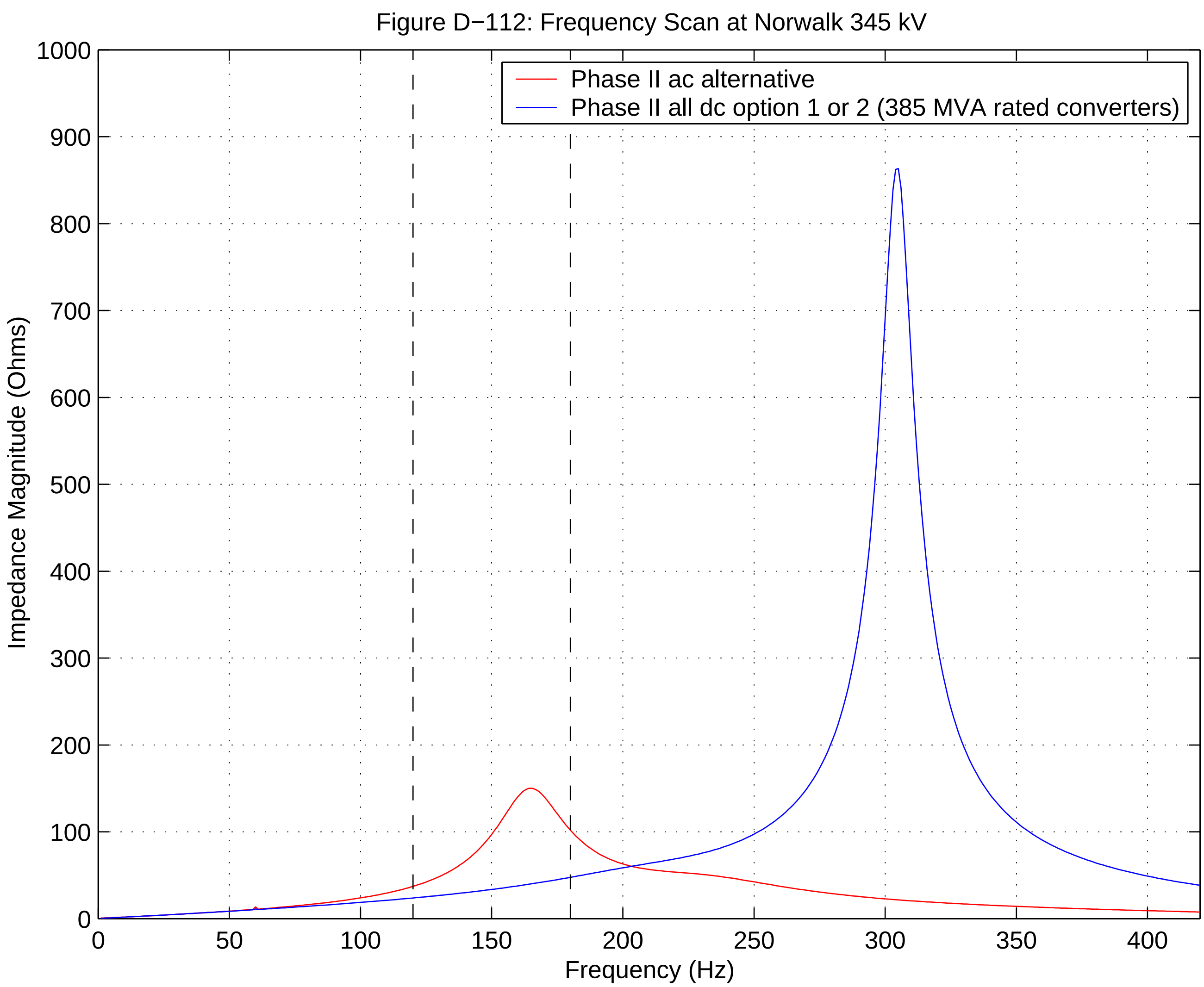


Figure D−112: Frequency Scan at Norwalk 345 kV
Phase II ac alternative
Phase II all dc option 1 or 2 (385 MVA rated converters)
Impedance Magnitude (Ohms)
Frequency (Hz)
0
100
200
300
400
500
600
700
800
900
1000
0
50
100
150
200
250
300
350
400

Figure D−113: Frequency Scan at Beseck 345 kV

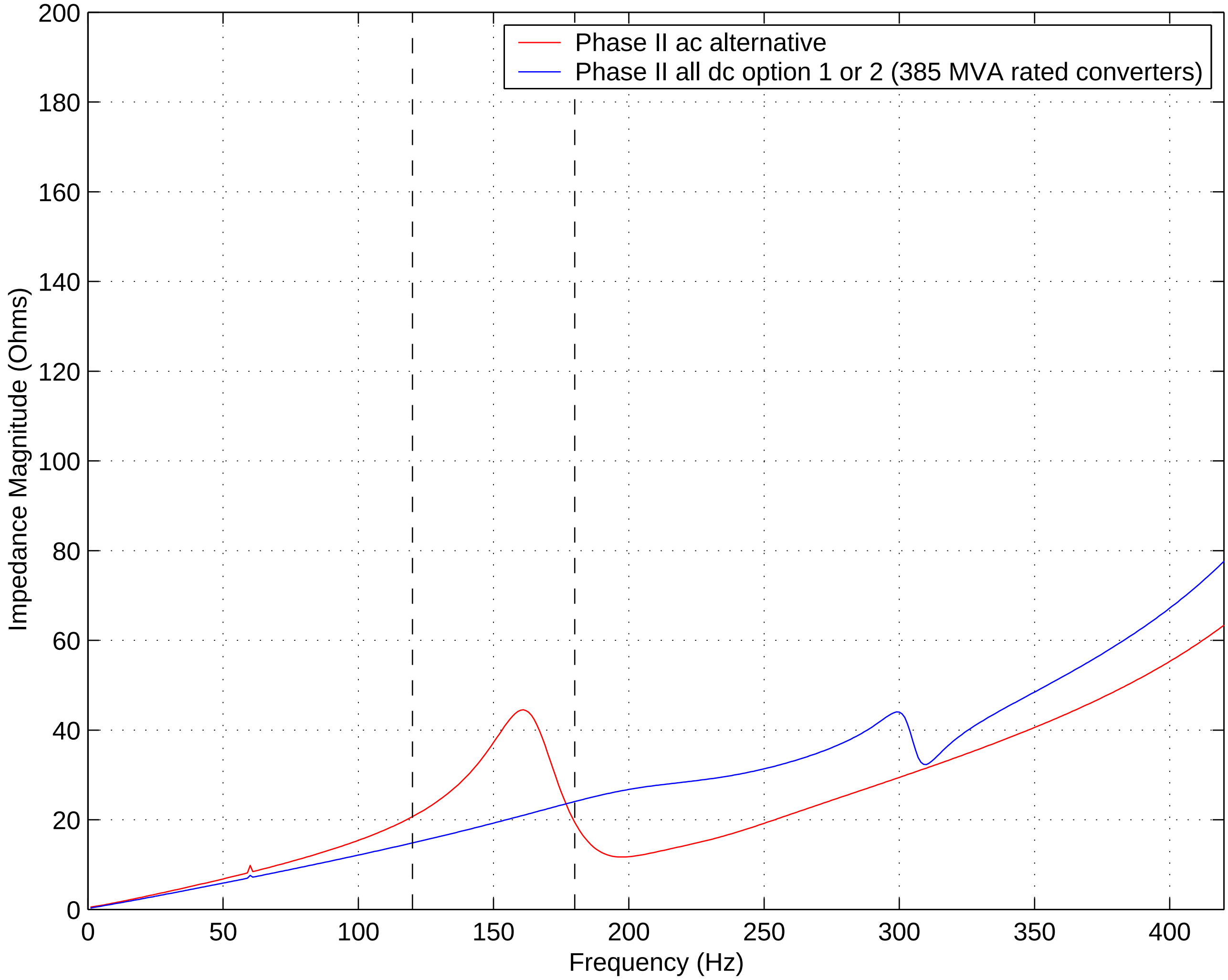
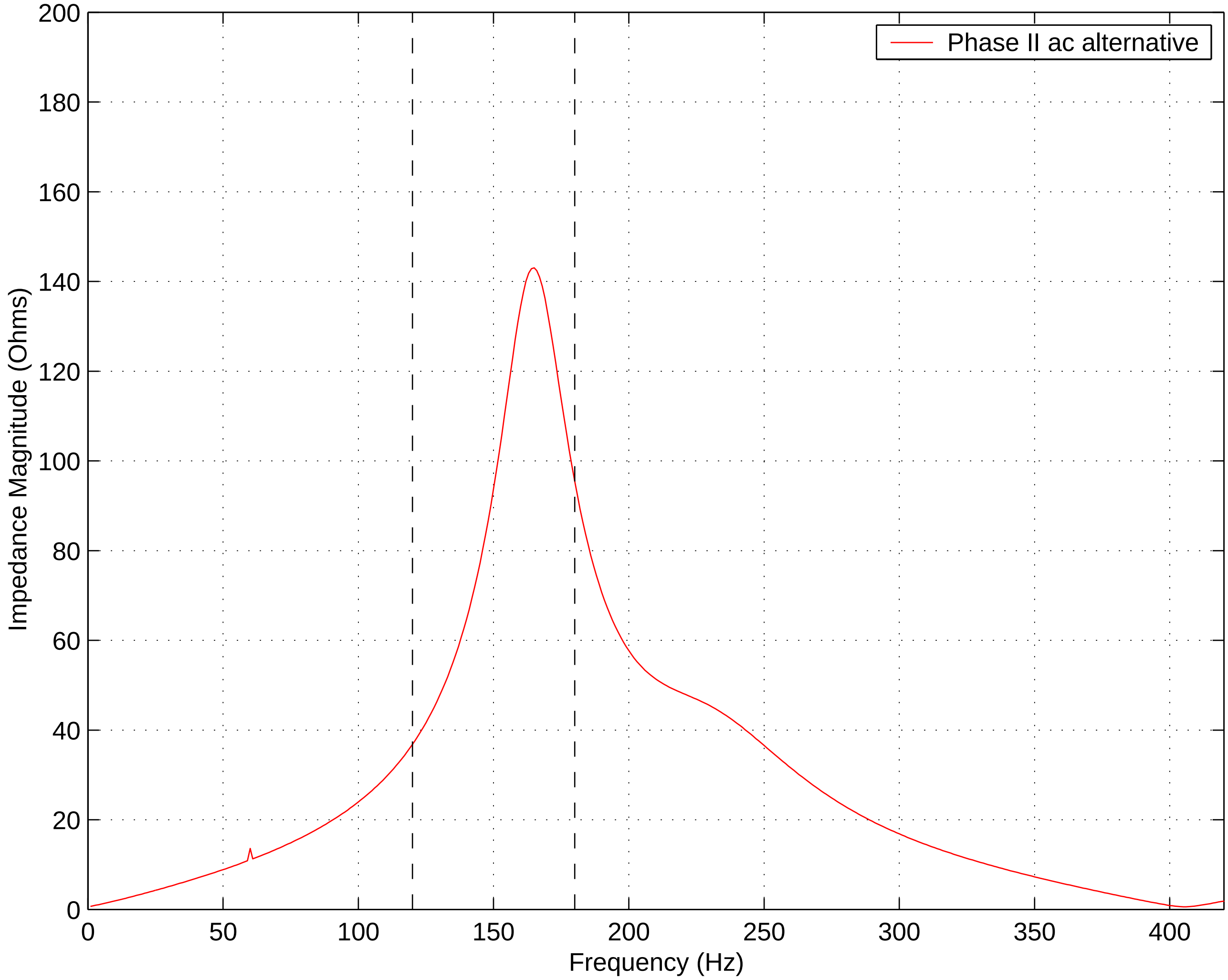


Figure D−114: Frequency Scan at Devon 345 kV



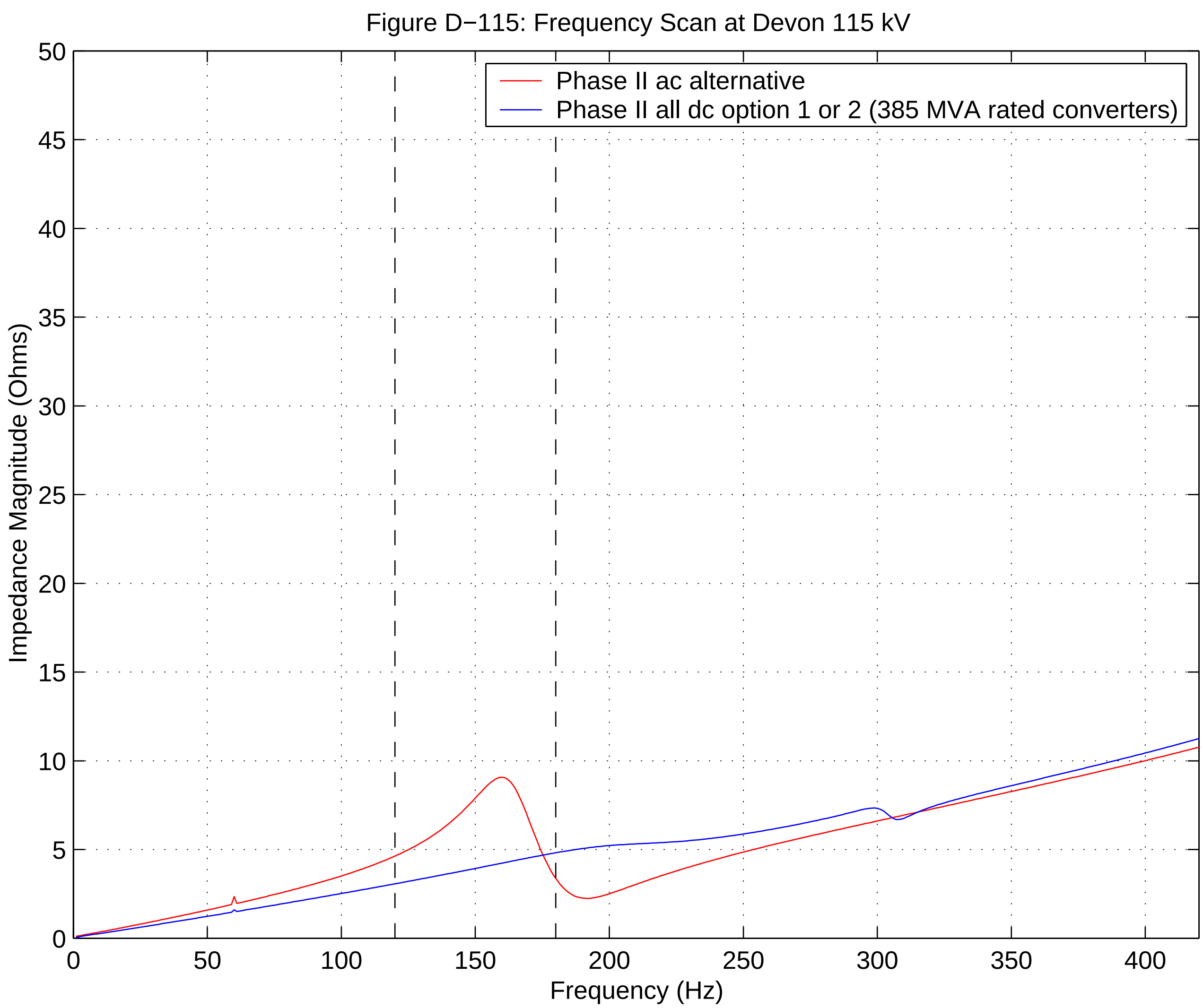


Figure D−115: Frequency Scan at Devon 115 kV
Phase II ac alternative
Phase II all dc option 1 or 2 (385 MVA rated converters)
Impedance Magnitude (Ohms)
Frequency (Hz)
0
5
10
15
20
25
30
35
40
45
50
0
50
100
150
200
250
300
350
400

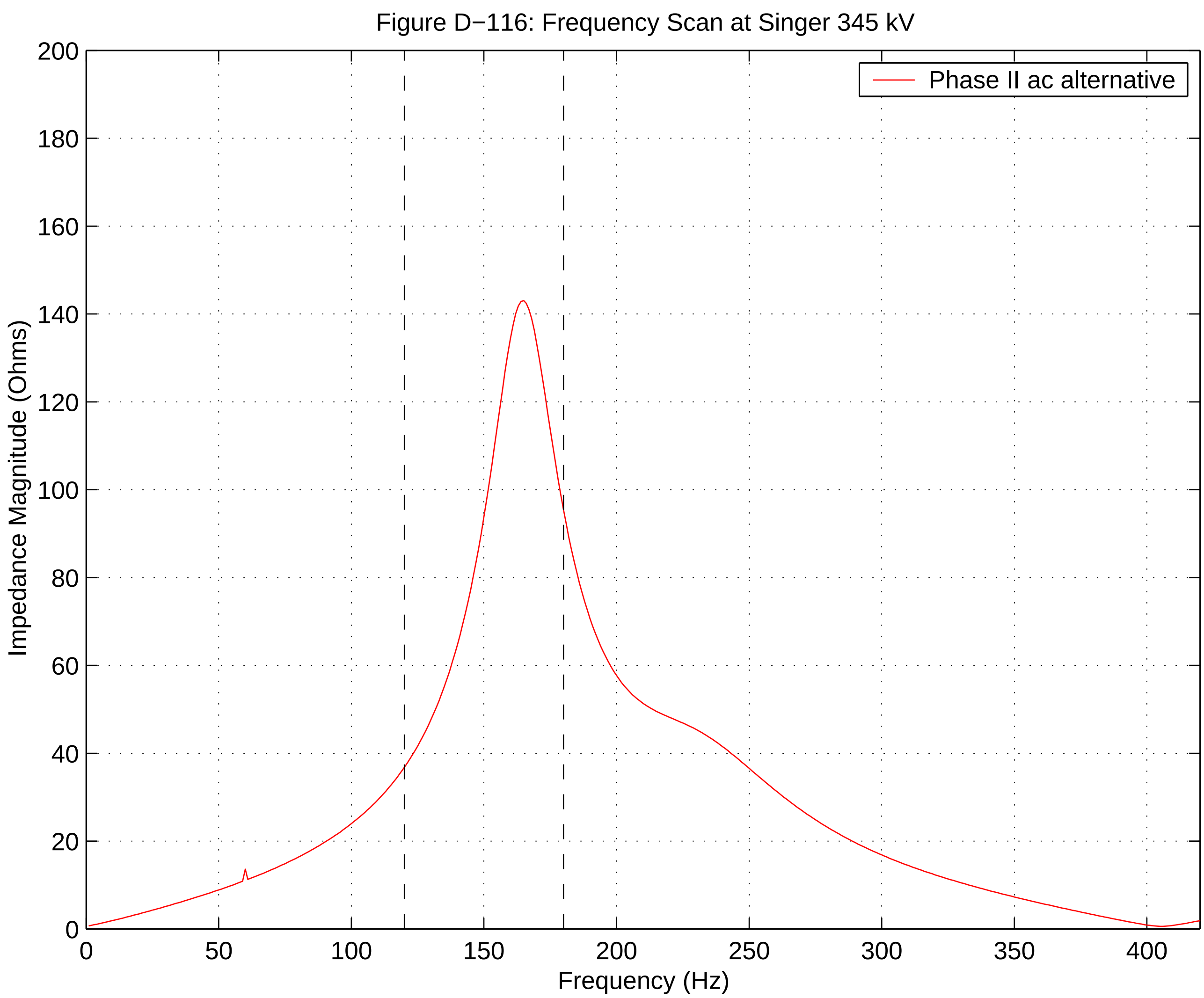


Figure D−116: Frequency Scan at Singer 345 kV
Phase II ac alternative
Impedance Magnitude (Ohms)
Frequency (Hz)
0
20
40
60
80
100
120
140
160
180
200
0
50
100
150
200
250
300
350
400

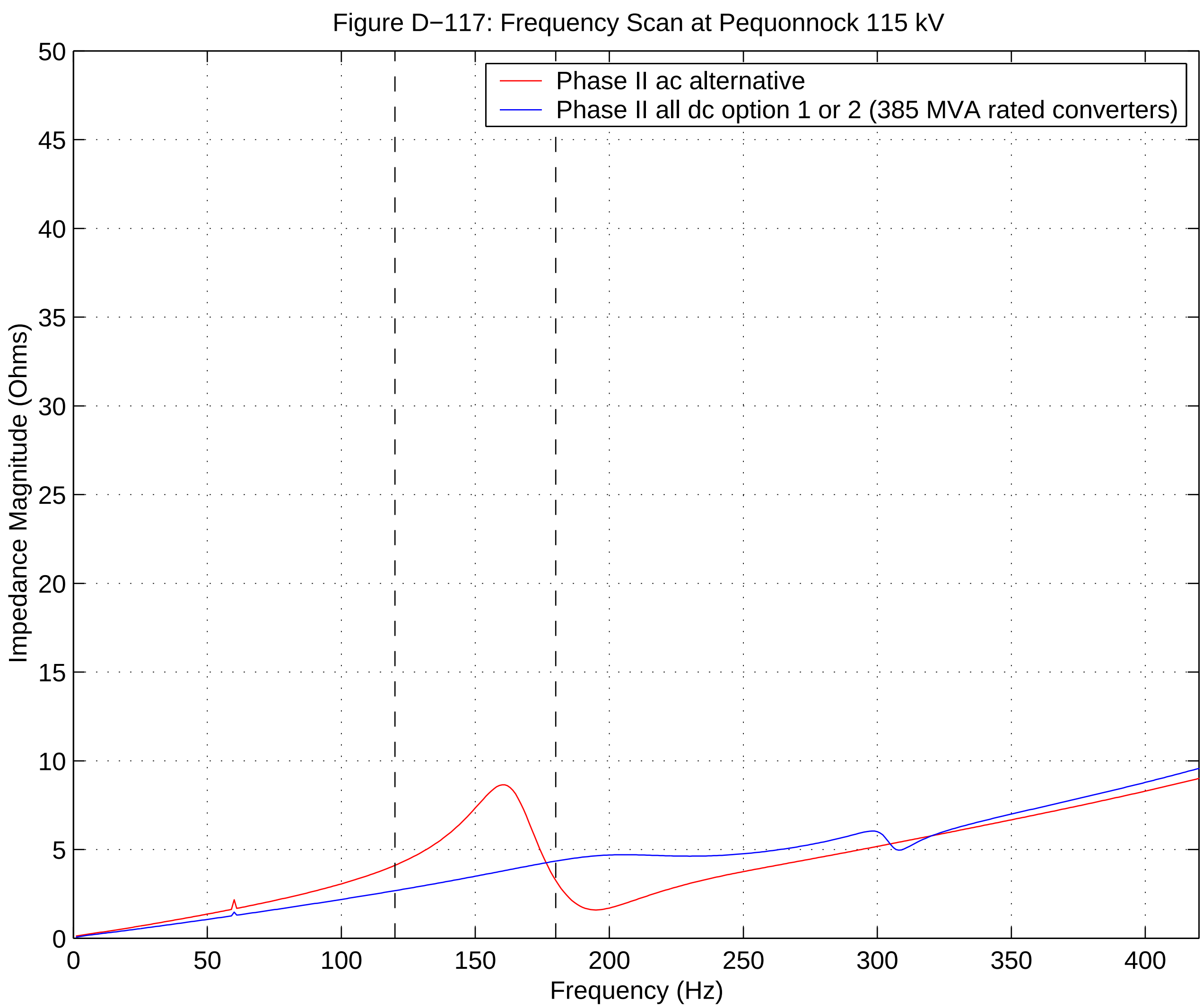


Figure D−117: Frequency Scan at Pequonnock 115 kV
Phase II ac alternative
Phase II all dc option 1 or 2 (385 MVA rated converters)
Impedance Magnitude (Ohms)
Frequency (Hz)
0
5
10
15
20
25
30
35
40
45
50
0
50
100
150
200
250
300
350
400

Figure D−118: Frequency Scan at Plumtree 345 kV

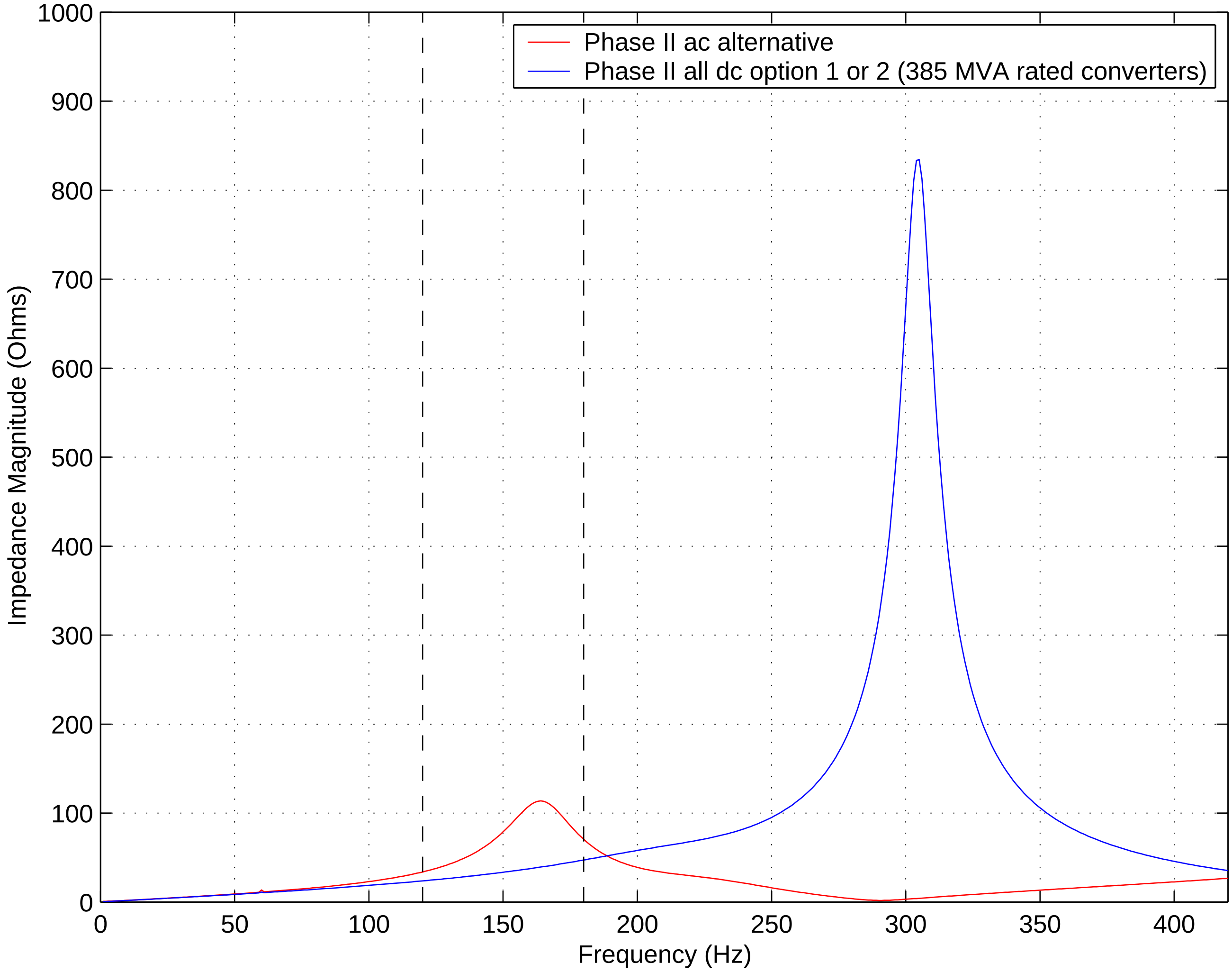
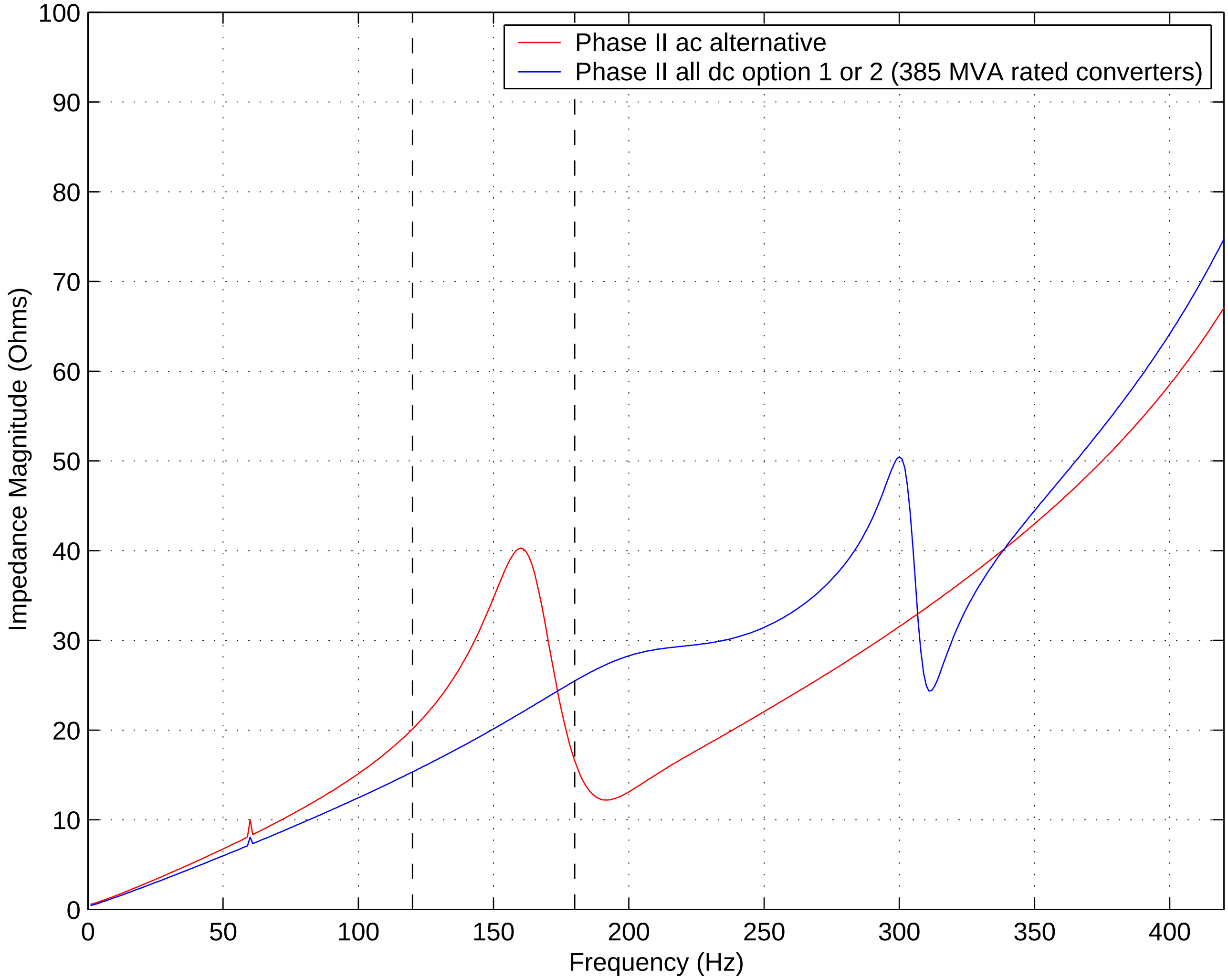


Figure D−119: Frequency Scan at Southington 345 kV



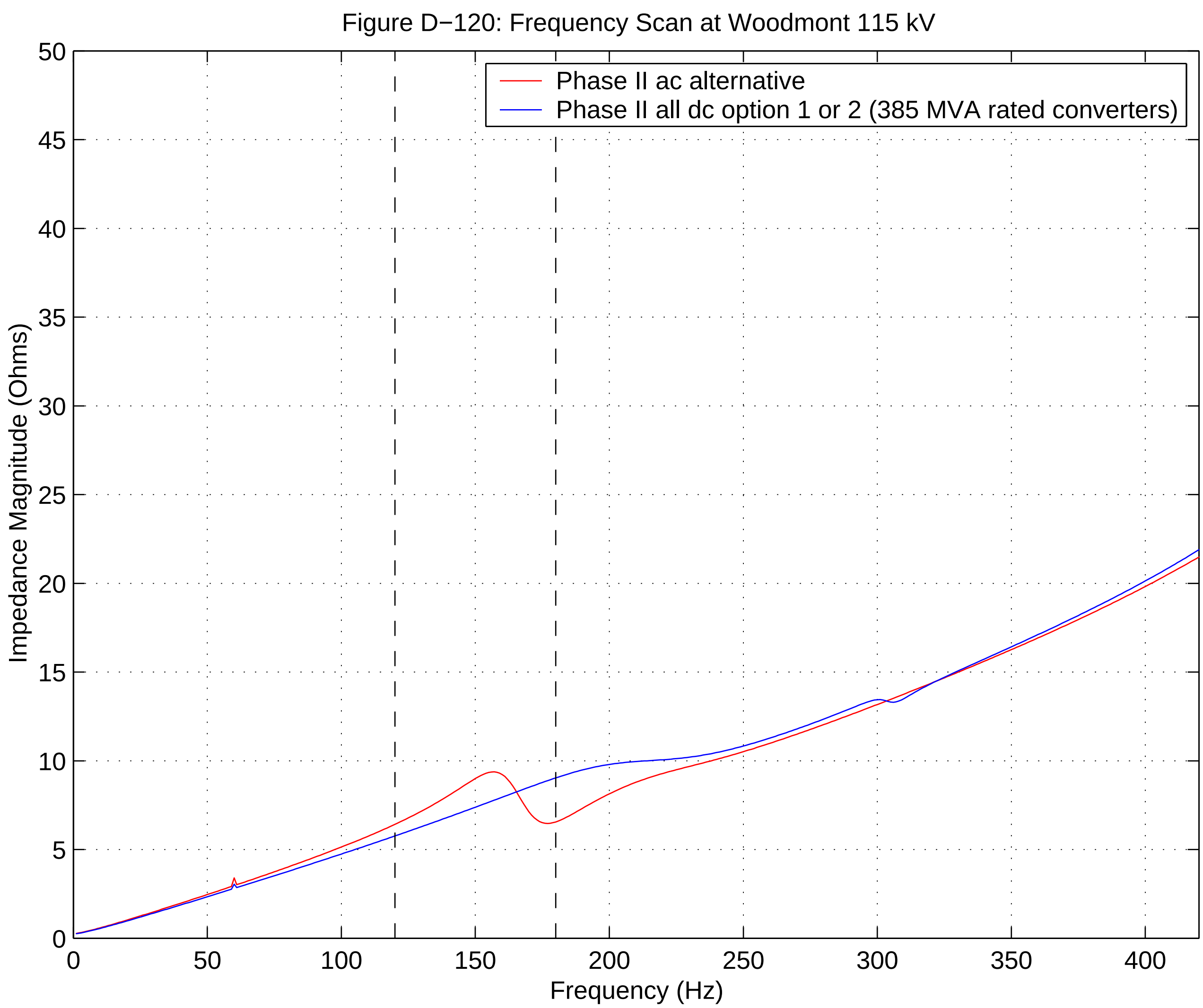


Figure D−120: Frequency Scan at Woodmont 115 kV
Phase II ac alternative
Phase II all dc option 1 or 2 (385 MVA rated converters)
Impedance Magnitude (Ohms)
Frequency (Hz)
0
5
10
15
20
25
30
35
40
45
50
0
50
100
150
200
250
300
350
400

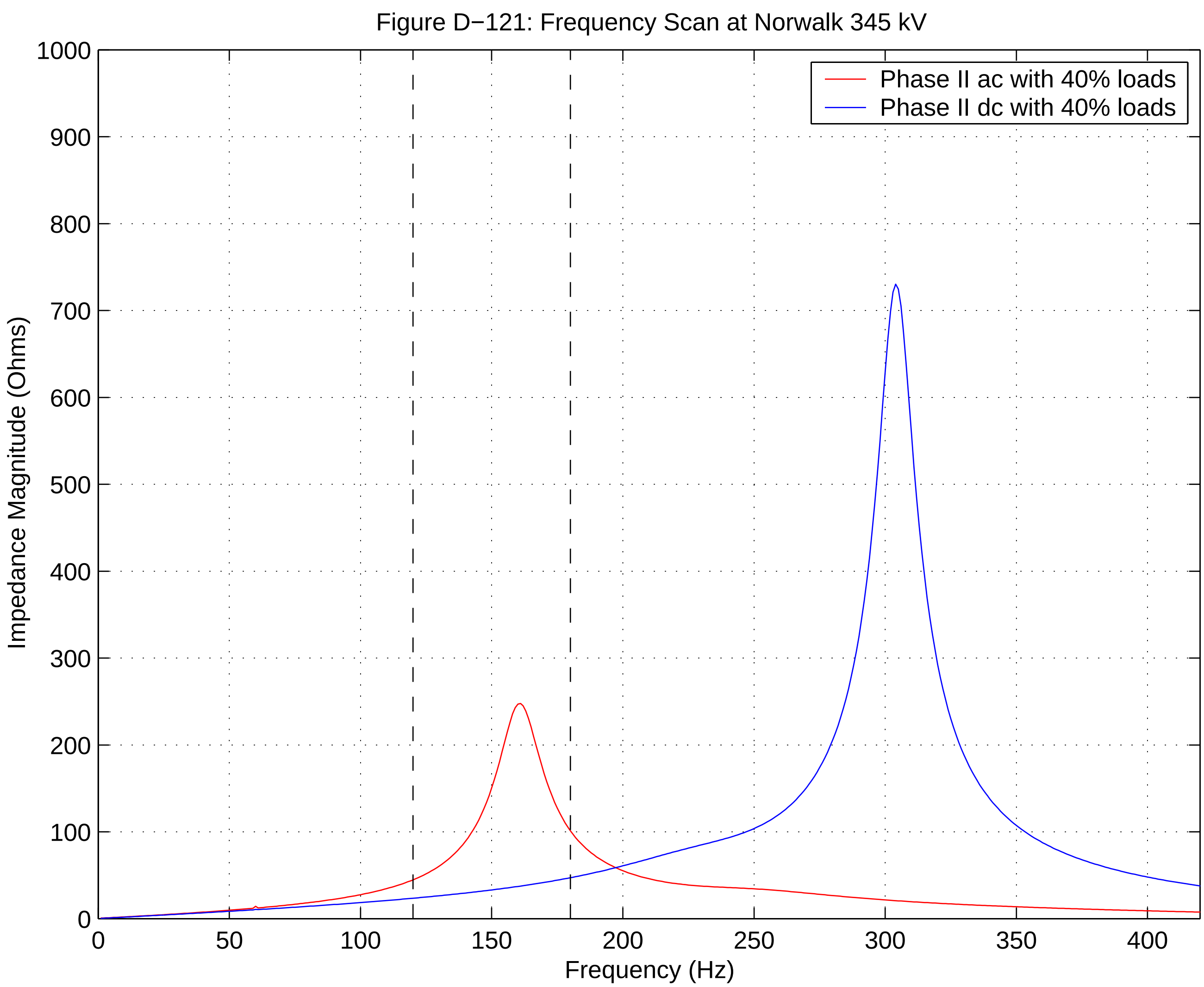
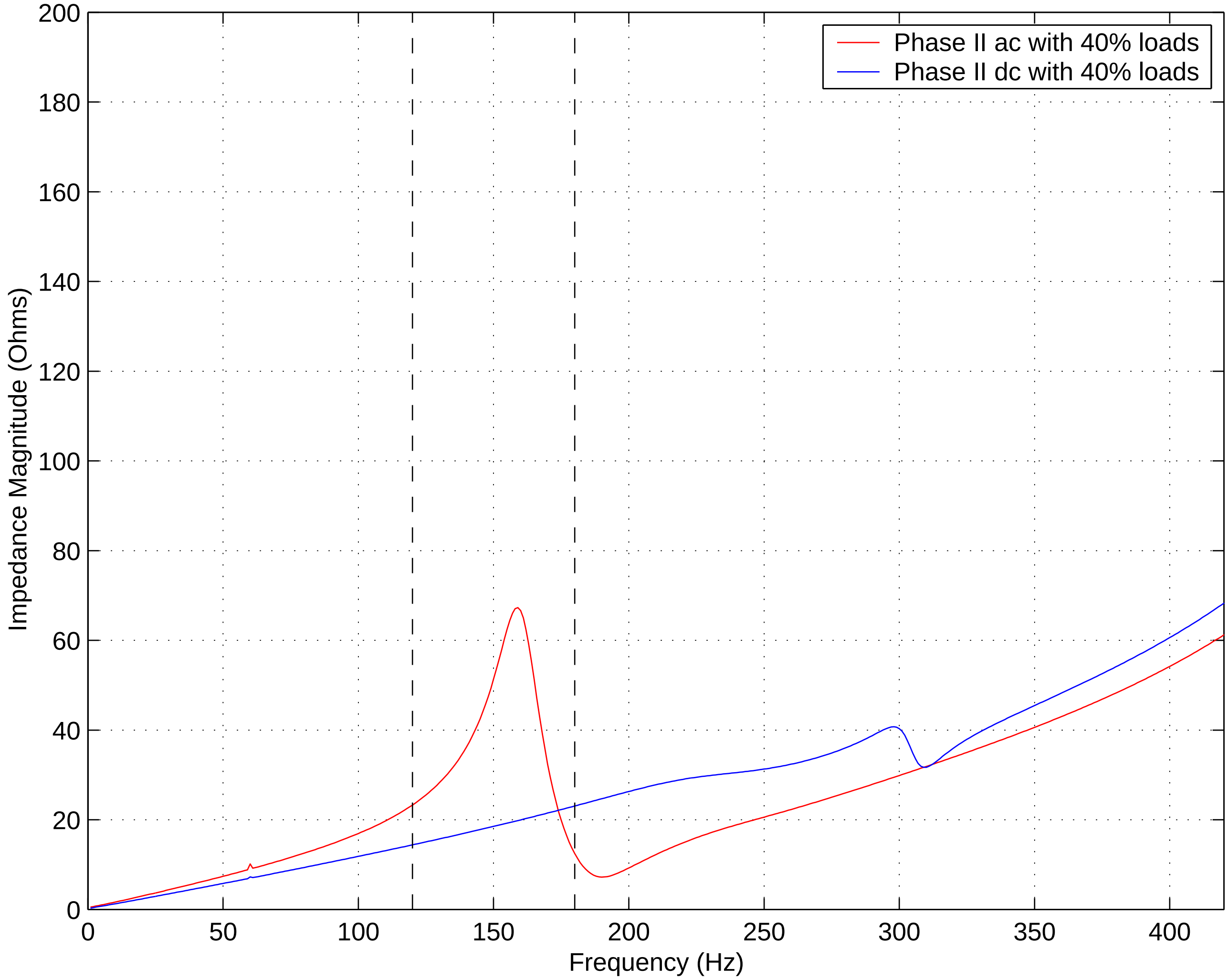


Figure D−121: Frequency Scan at Norwalk 345 kV
Phase II ac with 40% loads
Phase II dc with 40% loads
Impedance Magnitude (Ohms)
Frequency (Hz)
0
100
200
300
400
500
600
700
800
900
1000
0
50
100
150
200
250
300
350
400

Figure D−122: Frequency Scan at Beseck 345 kV



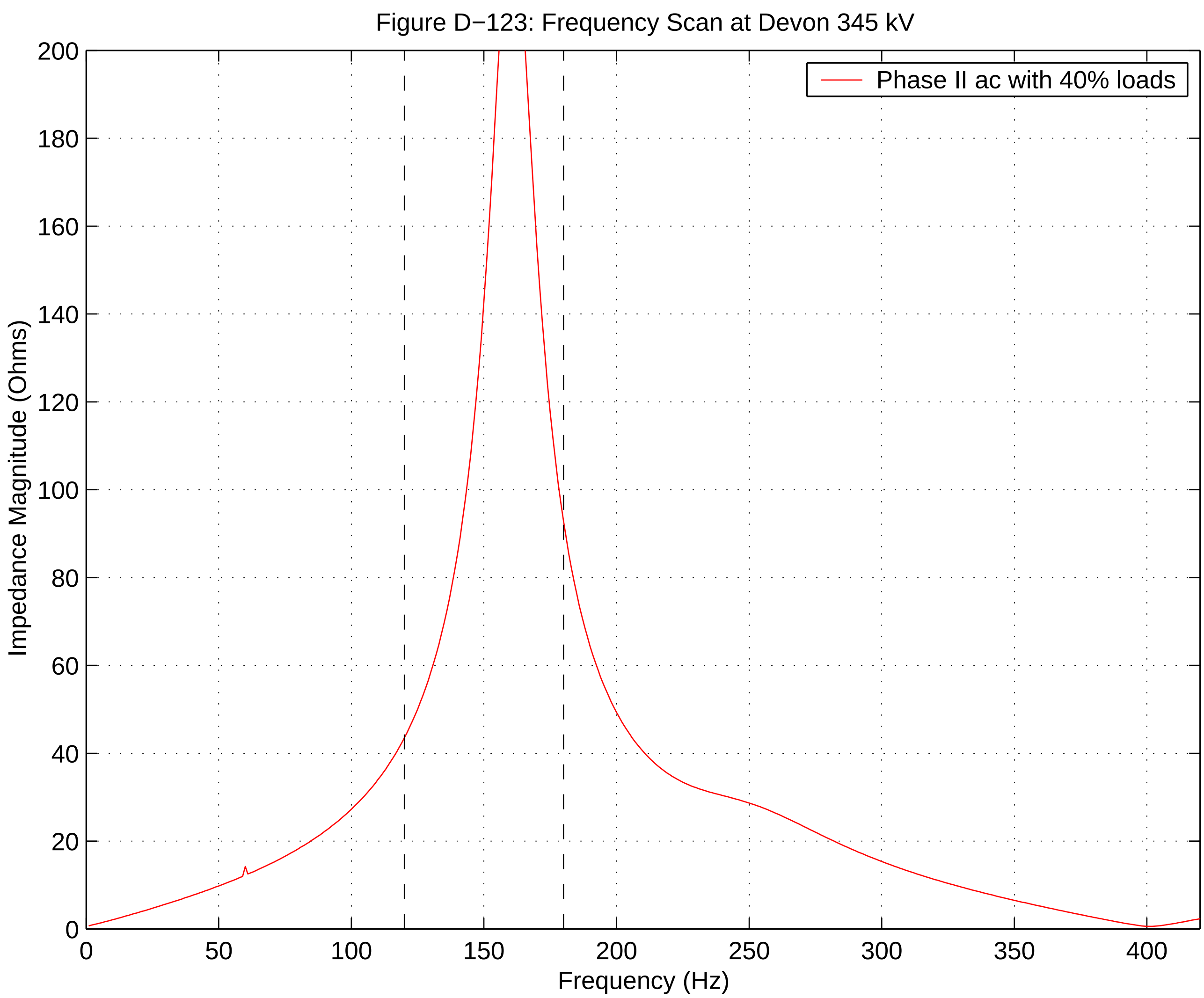


Figure D−123: Frequency Scan at Devon 345 kV
Phase II ac with 40% loads
Impedance Magnitude (Ohms)
Frequency (Hz)
0
20
40
60
80
100
120
140
160
180
200
0
50
100
150
200
250
300
350
400

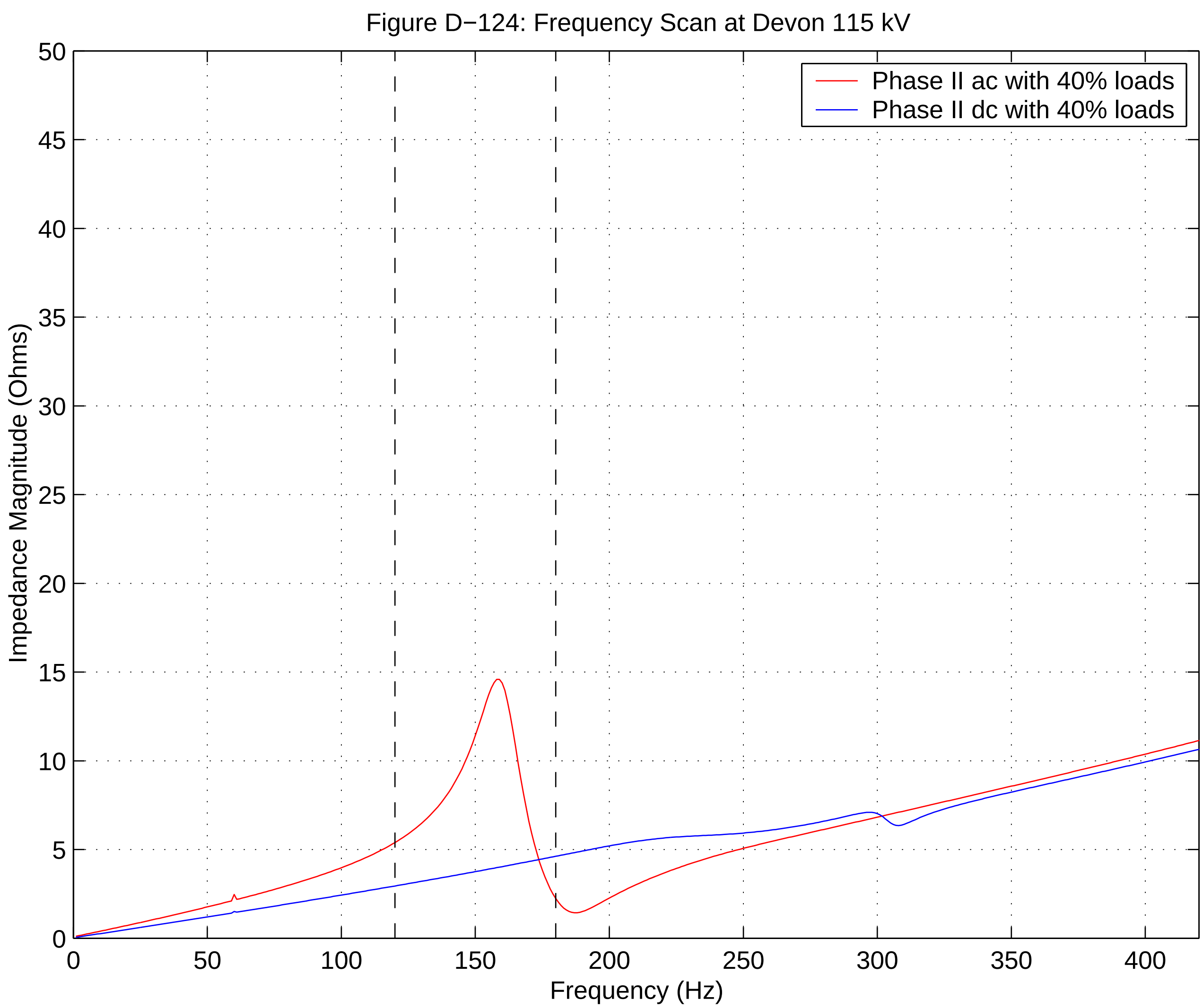


Figure D−124: Frequency Scan at Devon 115 kV
Phase II ac with 40% loads
Phase II dc with 40% loads
Impedance Magnitude (Ohms)
Frequency (Hz)
0
5
10
15
20
25
30
35
40
45
50
0
50
100
150
200
250
300
350
400

Figure D−125: Frequency Scan at Singer 345 kV

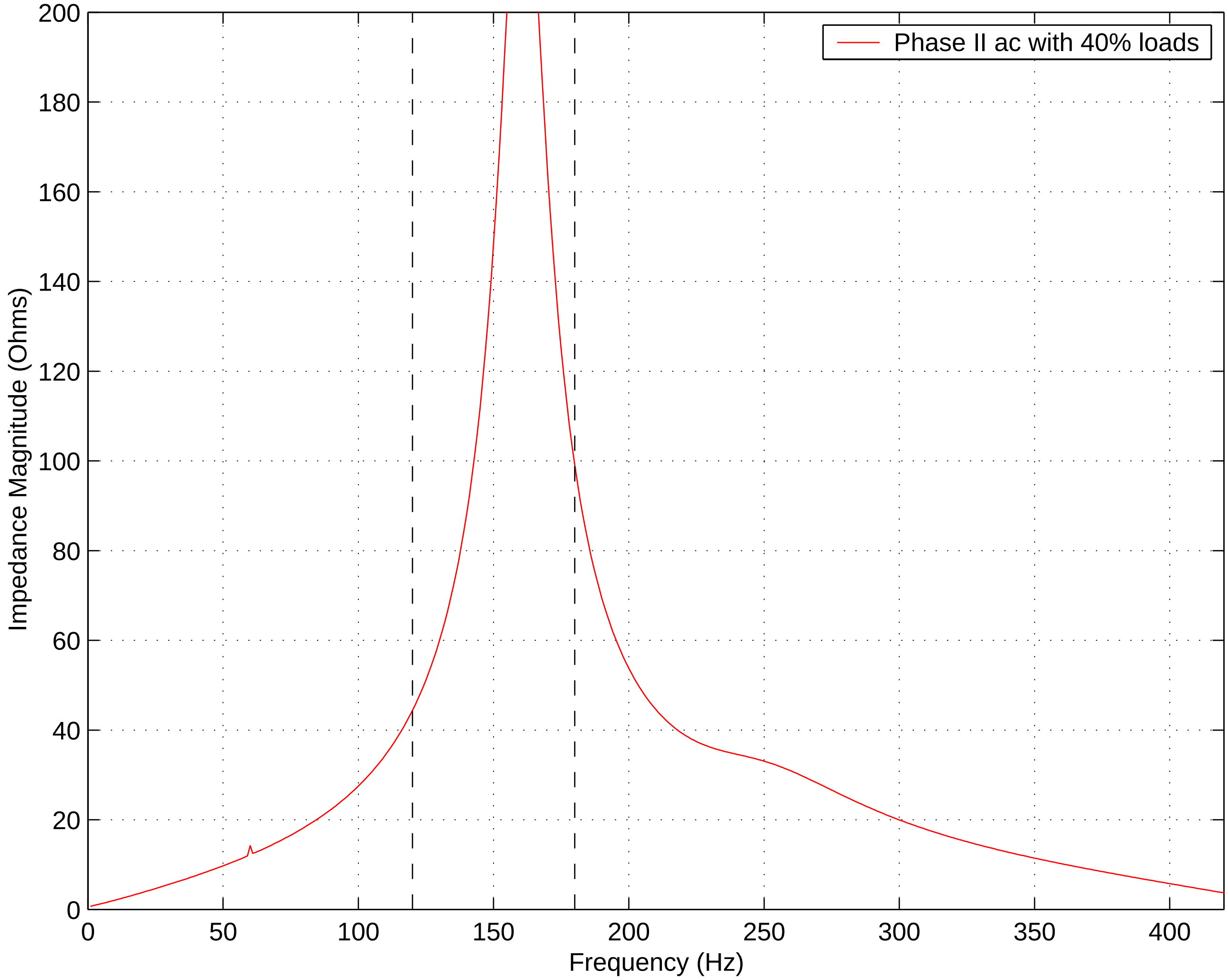


Figure D−126: Frequency Scan at Pequonnock 115 kV

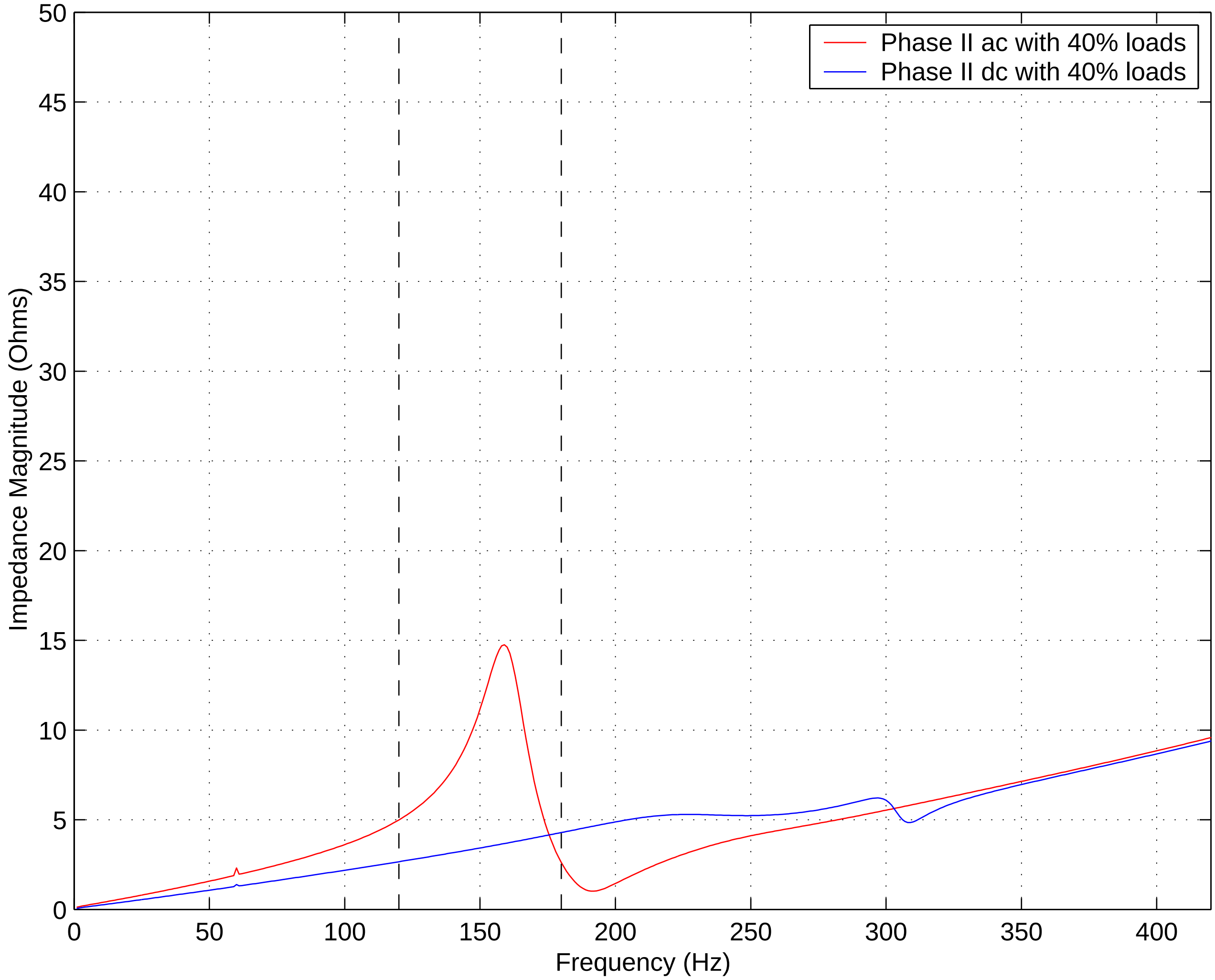
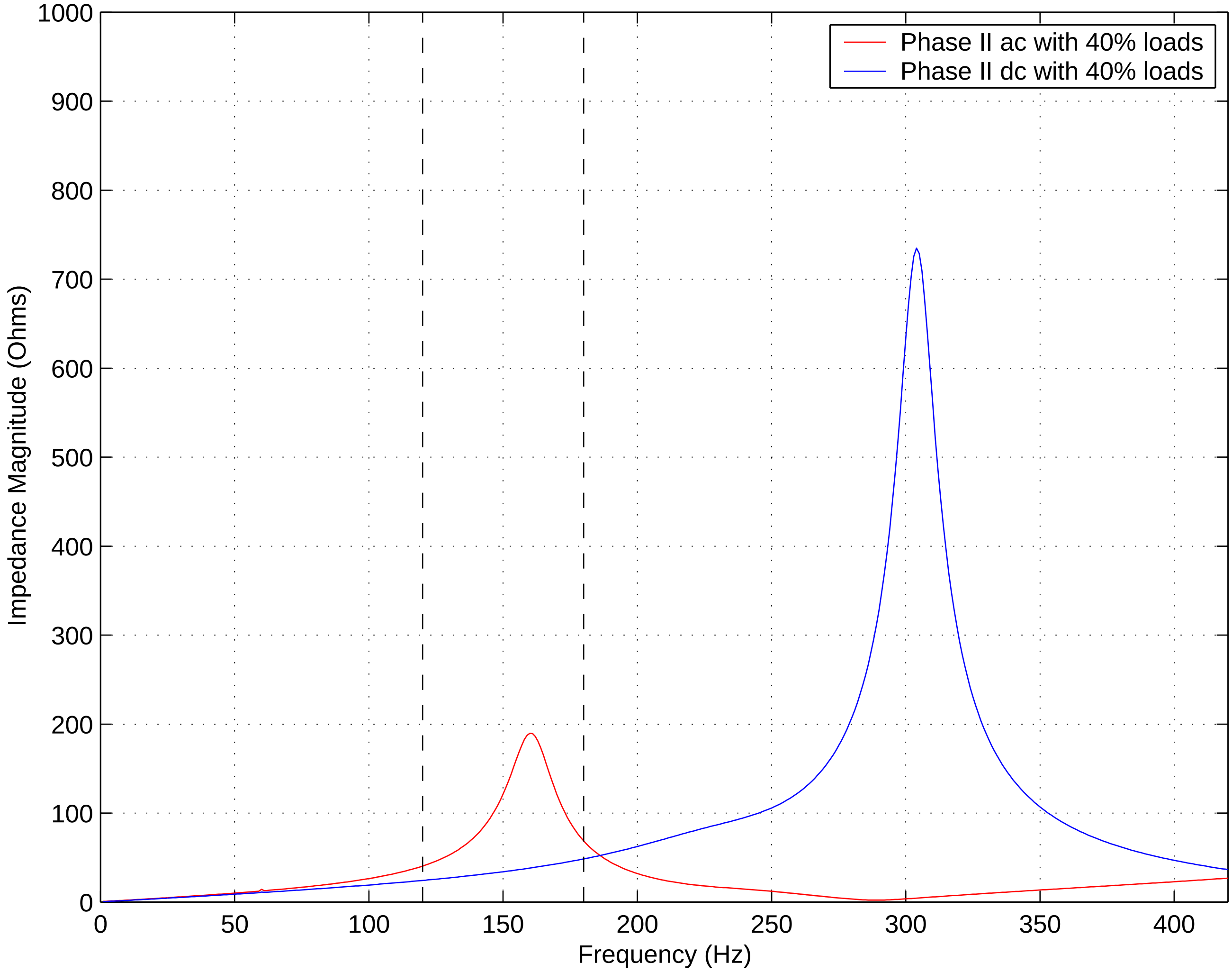


Figure D−127: Frequency Scan at Plumtree 345 kV



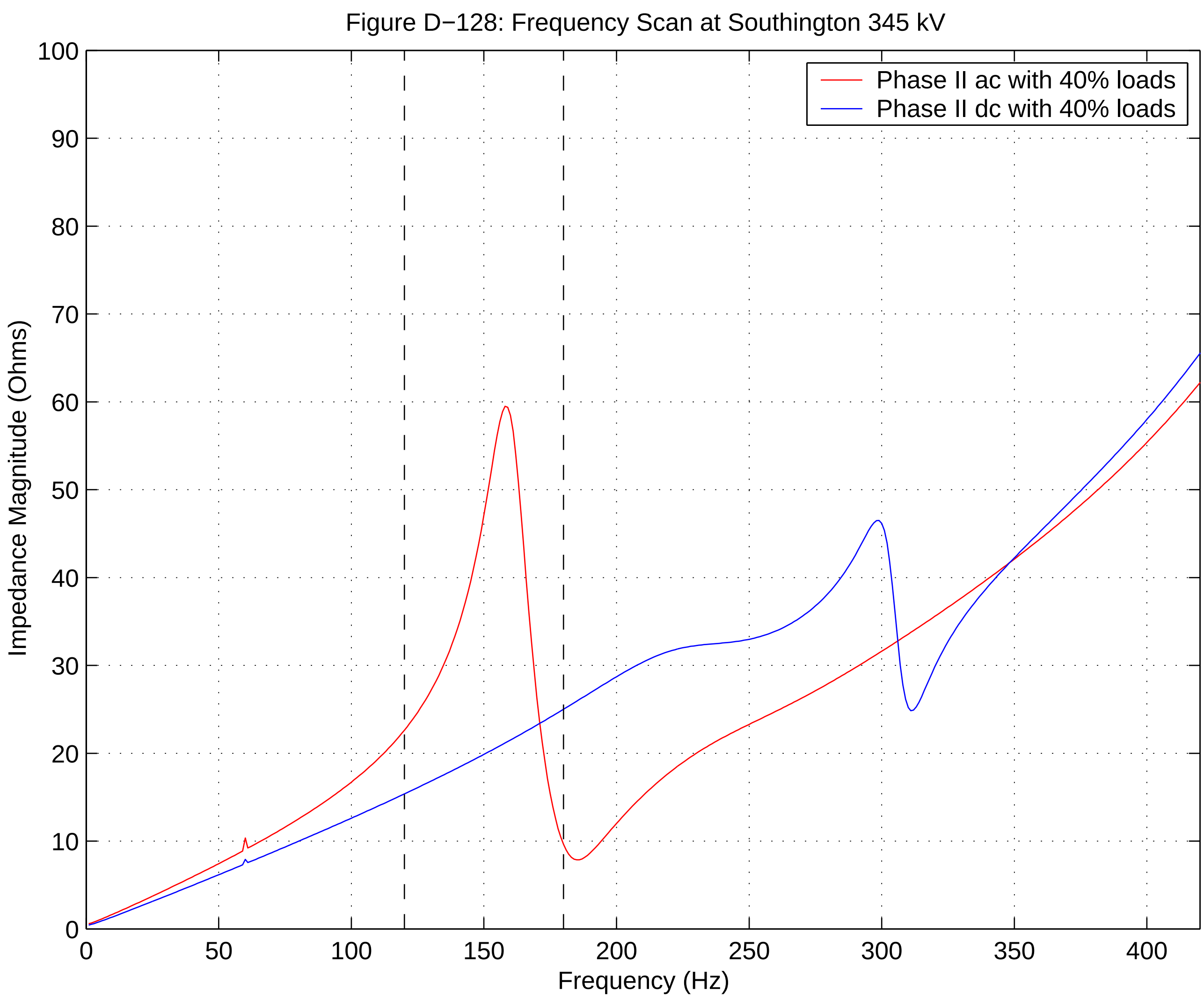


Figure D−128: Frequency Scan at Southington 345 kV
Phase II ac with 40% loads
Phase II dc with 40% loads
Impedance Magnitude (Ohms)
Frequency (Hz)
0
10
20
30
40
50
60
70
80
90
100
0
50
100
150
200
250
300
350
400

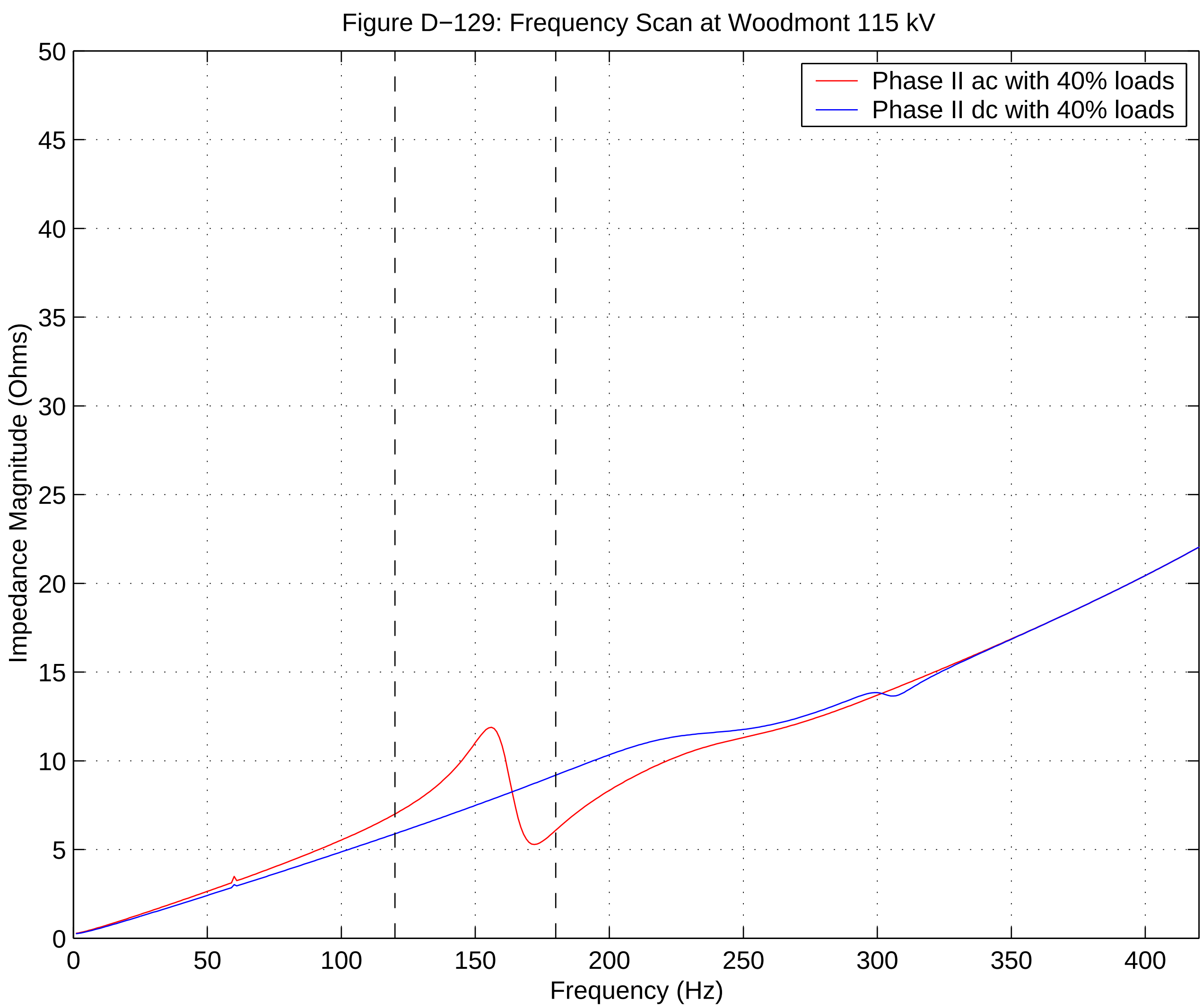
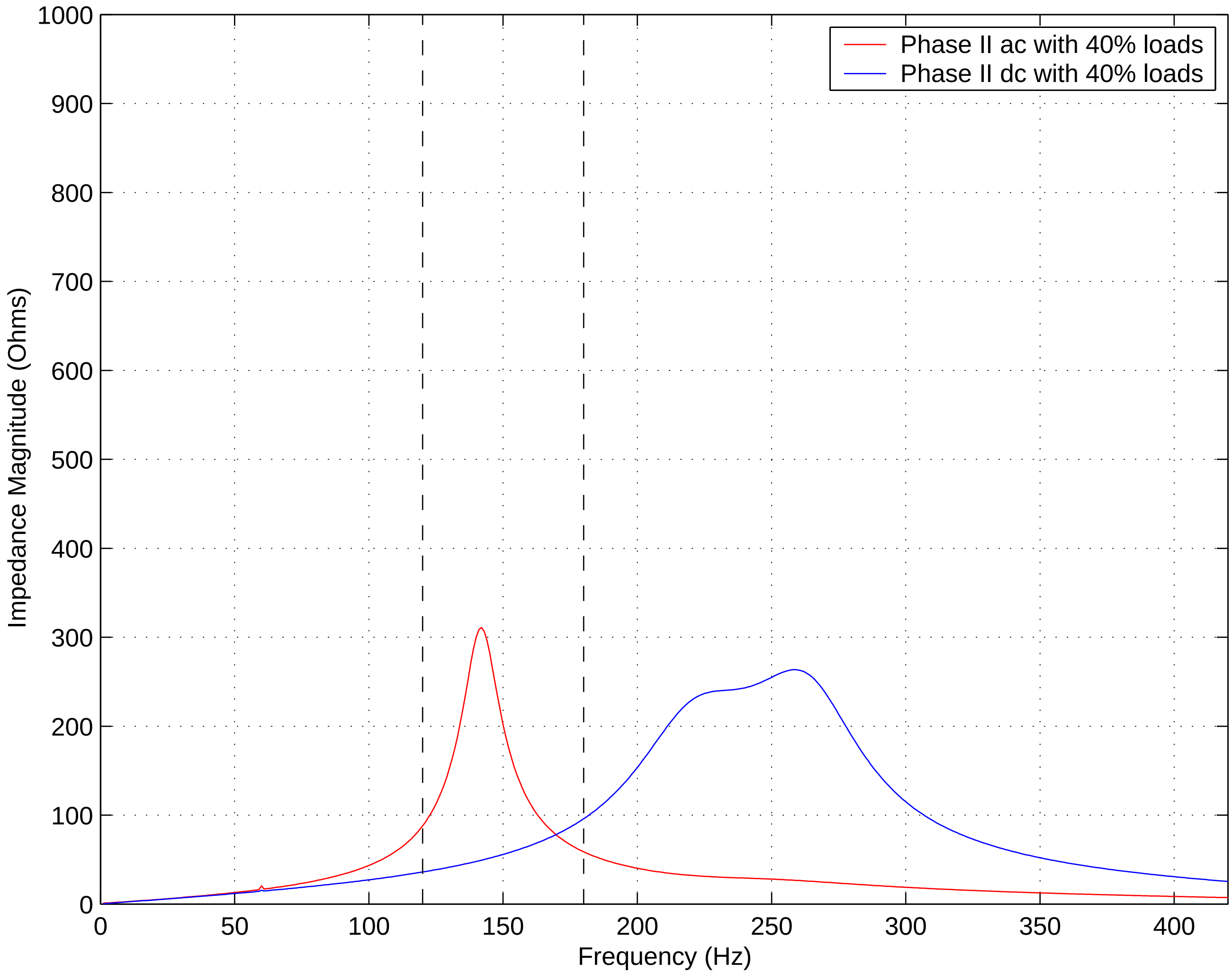


Figure D−129: Frequency Scan at Woodmont 115 kV
Phase II ac with 40% loads
Phase II dc with 40% loads
Impedance Magnitude (Ohms)
Frequency (Hz)
0
5
10
15
20
25
30
35
40
45
50
0
50
100
150
200
250
300
350
400

Figure D−130: Frequency Scan at Norwalk 345 kV − Cont 2



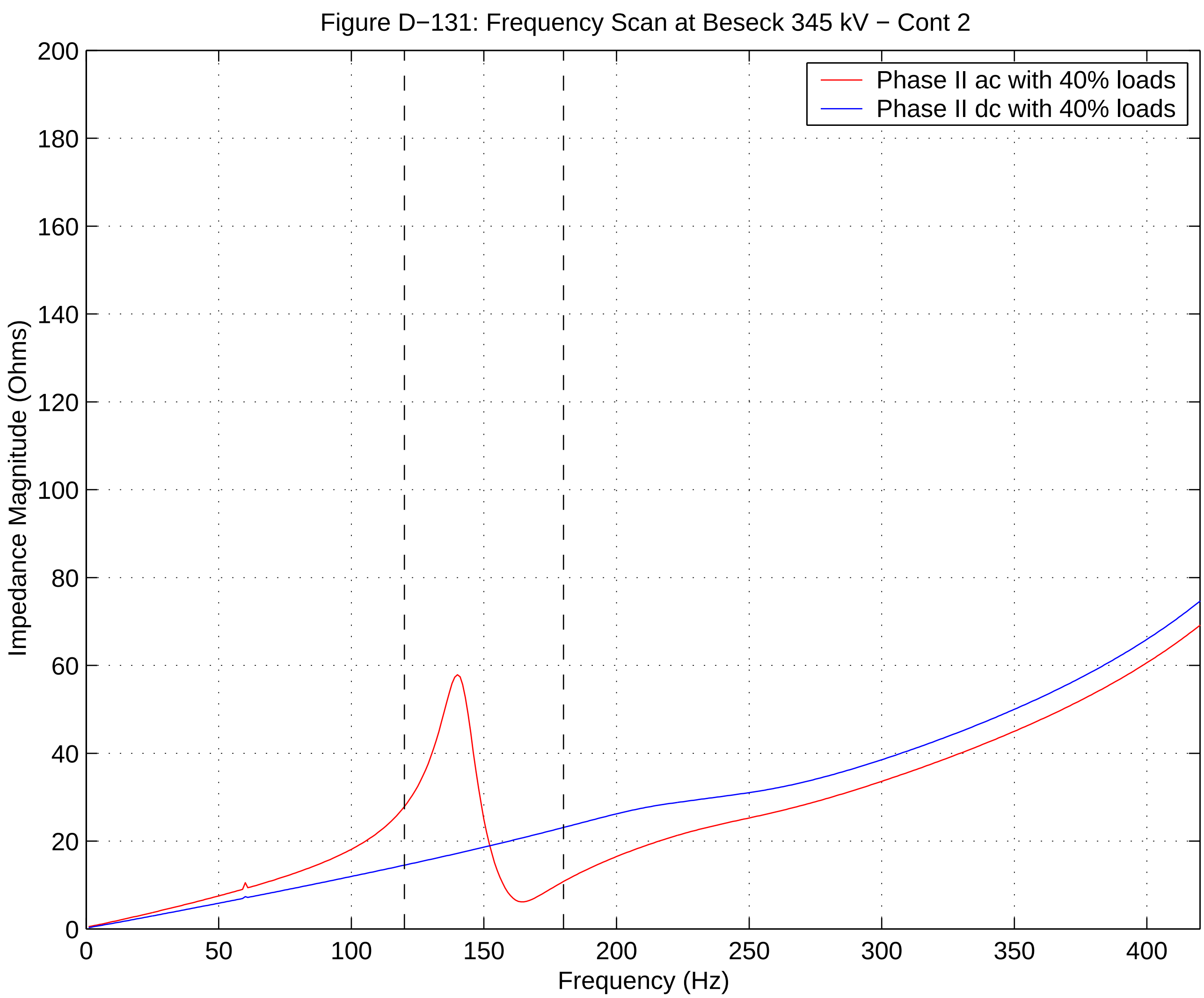


Figure D−131: Frequency Scan at Beseck 345 kV − Cont 2
Phase II ac with 40% loads
Phase II dc with 40% loads
Impedance Magnitude (Ohms)
Frequency (Hz)
0
20
40
60
80
100
120
140
160
180
200
0
50
100
150
200
250
300
350
400

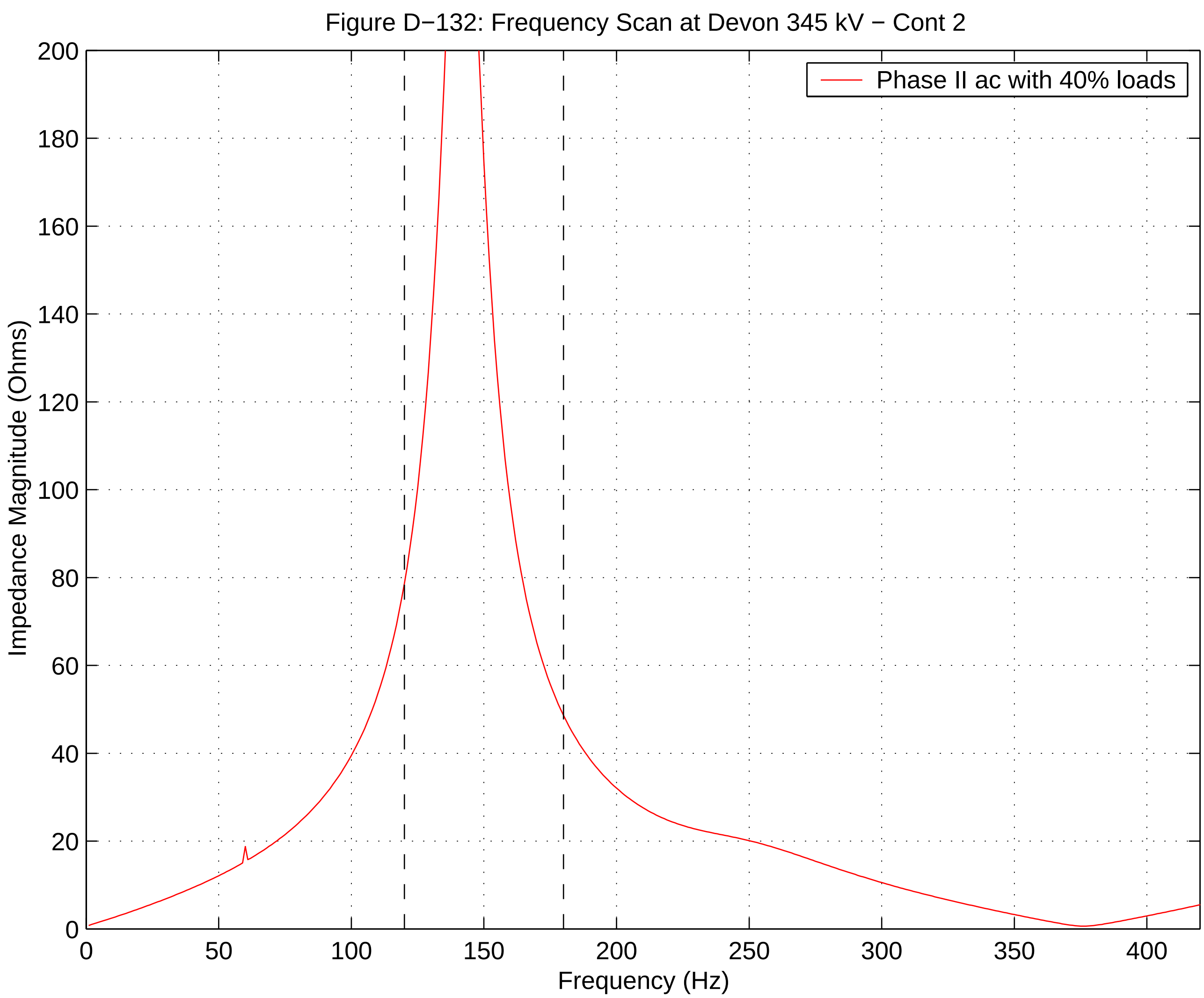
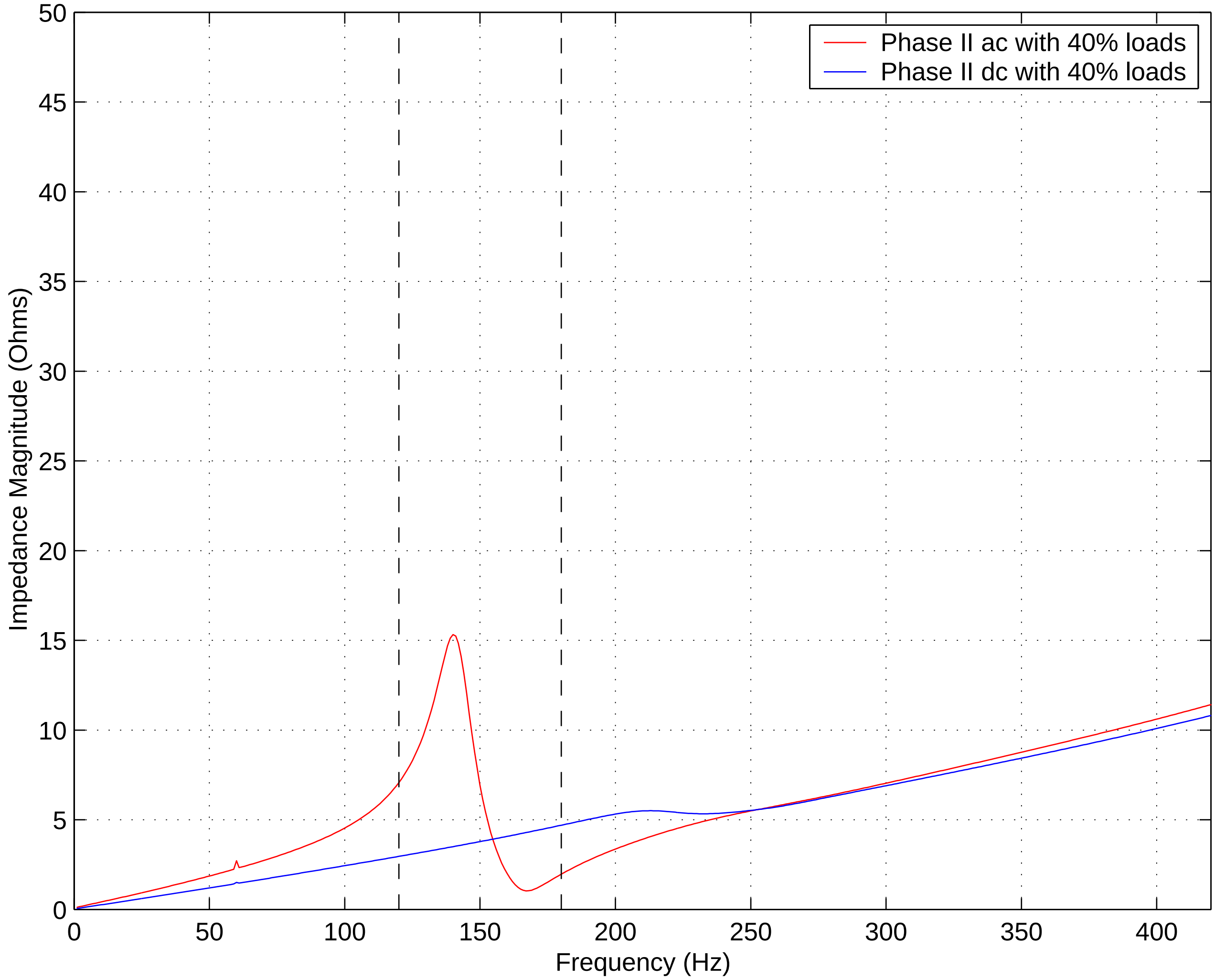


Figure D−132: Frequency Scan at Devon 345 kV − Cont 2
Phase II ac with 40% loads
Impedance Magnitude (Ohms)
Frequency (Hz)
0
20
40
60
80
100
120
140
160
180
200
0
50
100
150
200
250
300
350
400

Figure D−133: Frequency Scan at Devon 115 kV − Cont 2



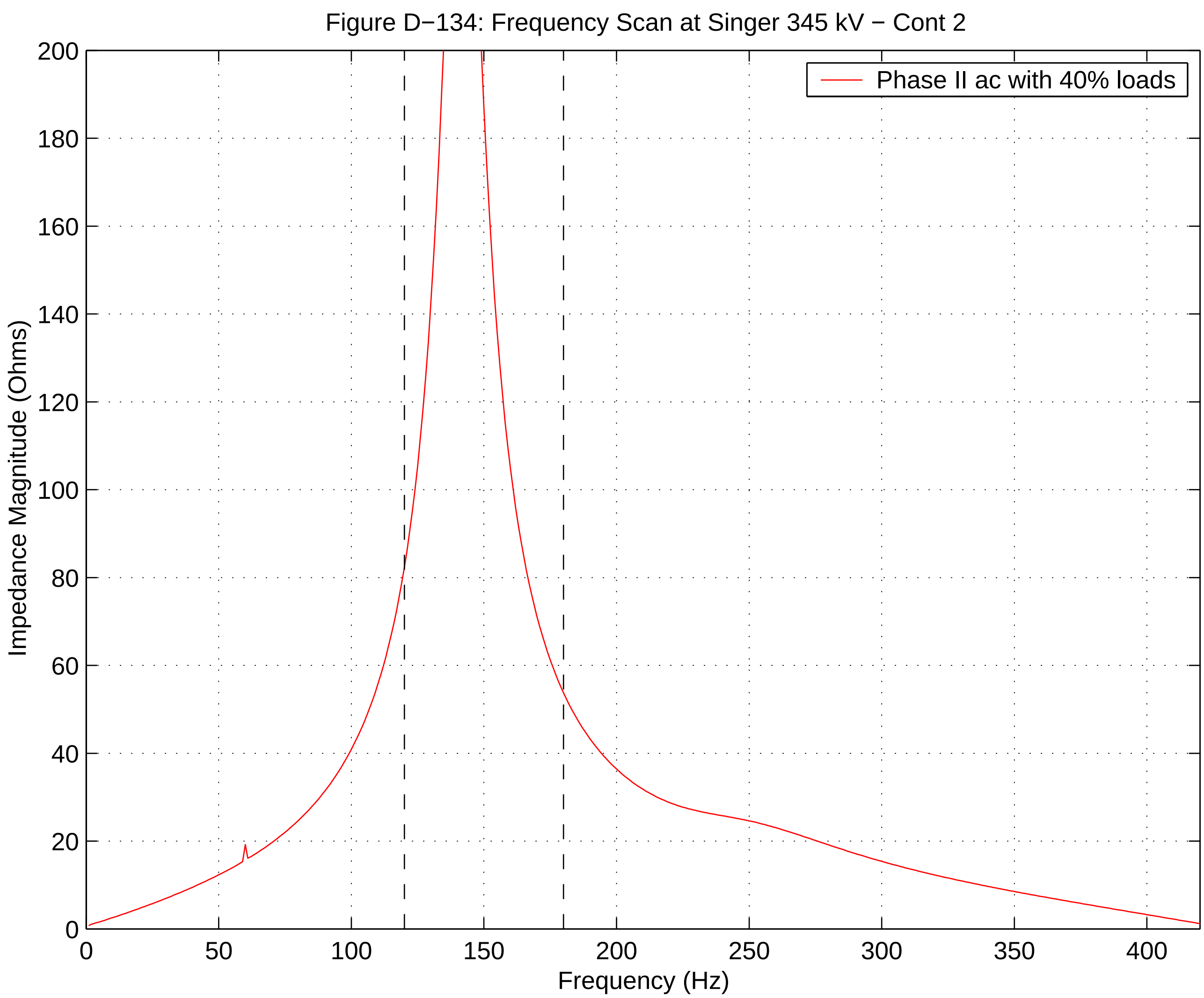


Figure D−134: Frequency Scan at Singer 345 kV − Cont 2
Phase II ac with 40% loads
Impedance Magnitude (Ohms)
Frequency (Hz)
0
20
40
60
80
100
120
140
160
180
200
0
50
100
150
200
250
300
350
400

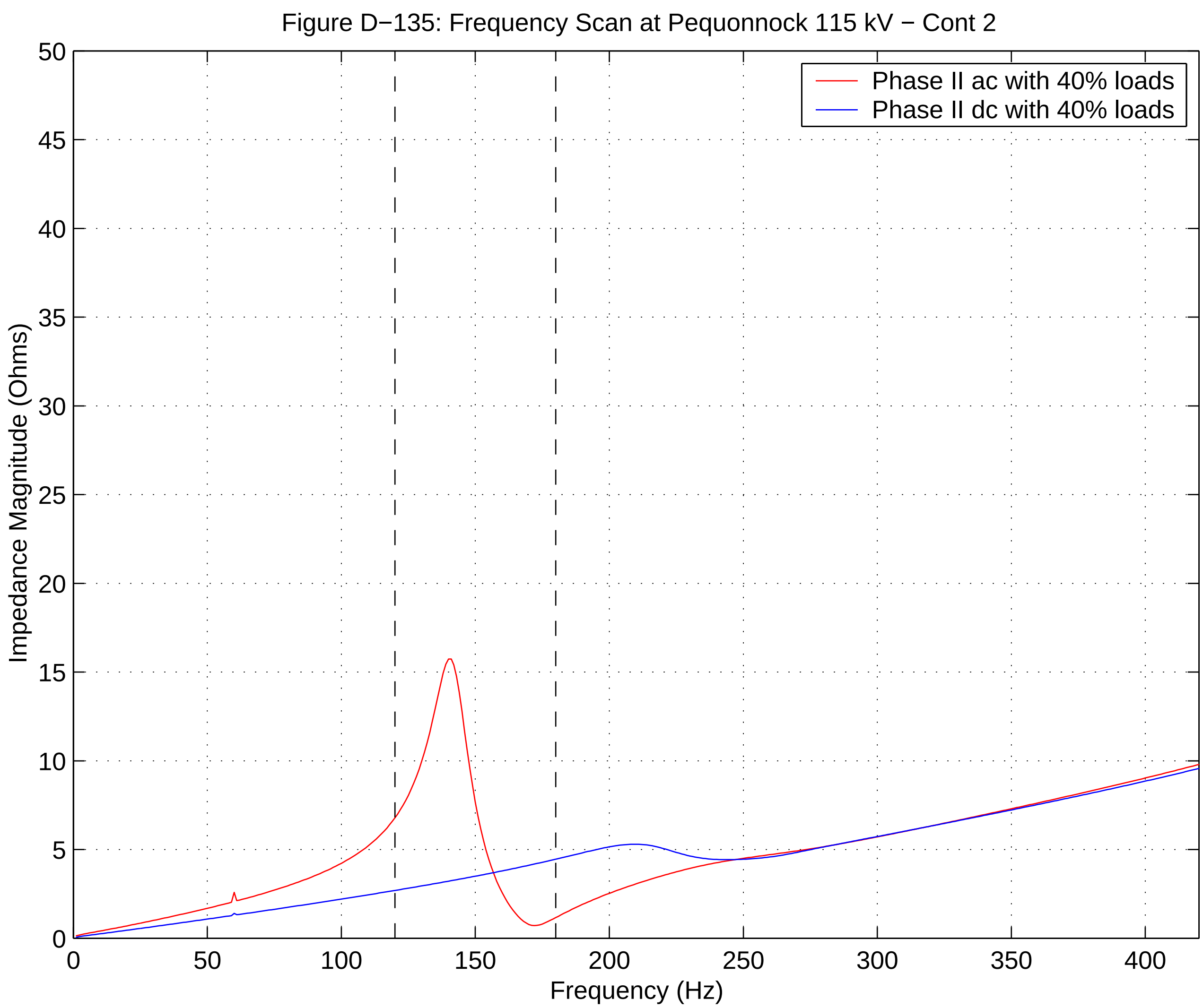
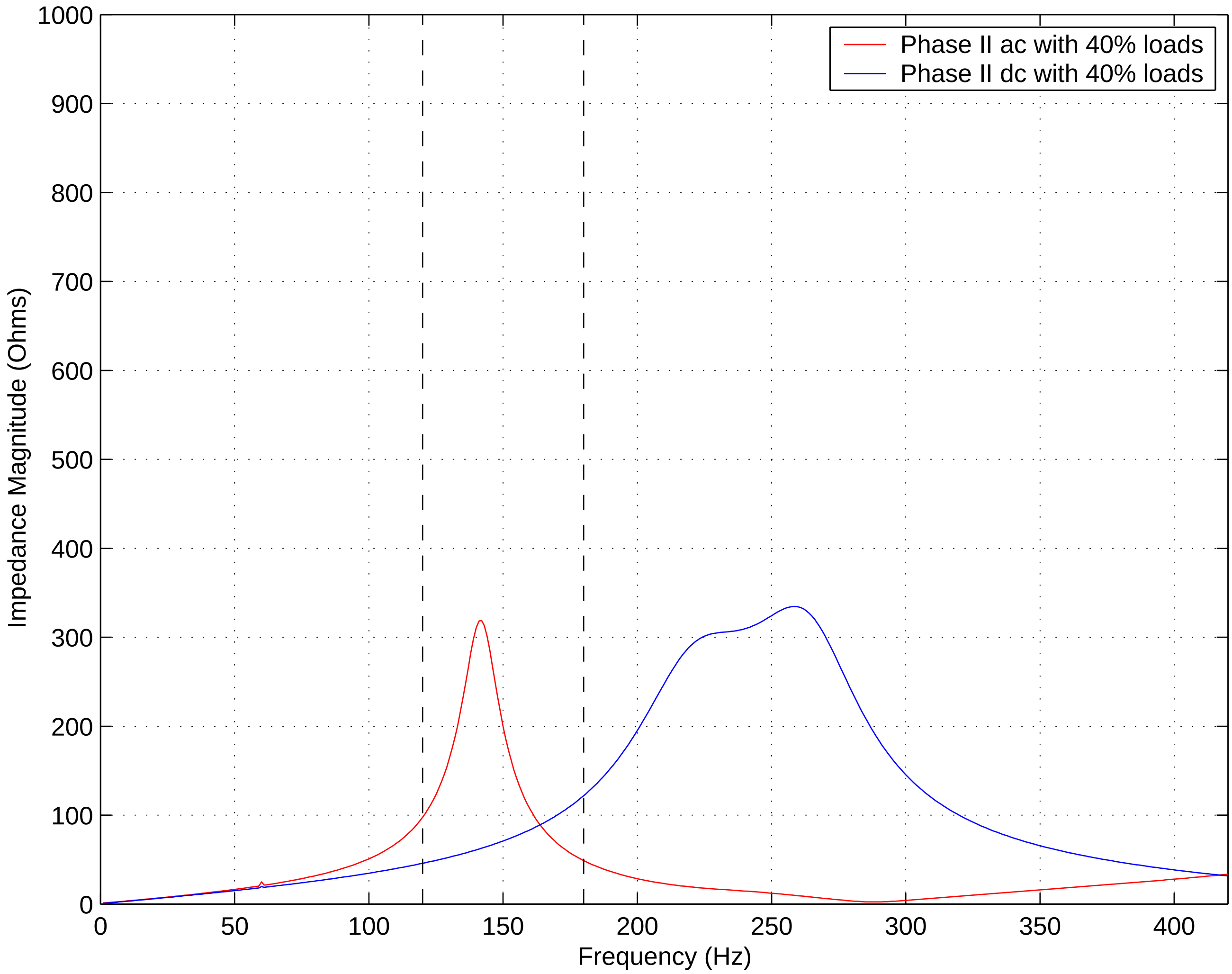


Figure D−135: Frequency Scan at Pequonnock 115 kV − Cont 2
Phase II ac with 40% loads
Phase II dc with 40% loads
Impedance Magnitude (Ohms)
Frequency (Hz)
0
5
10
15
20
25
30
35
40
45
50
0
50
100
150
200
250
300
350
400

Figure D−136: Frequency Scan at Plumtree 345 kV − Cont 2



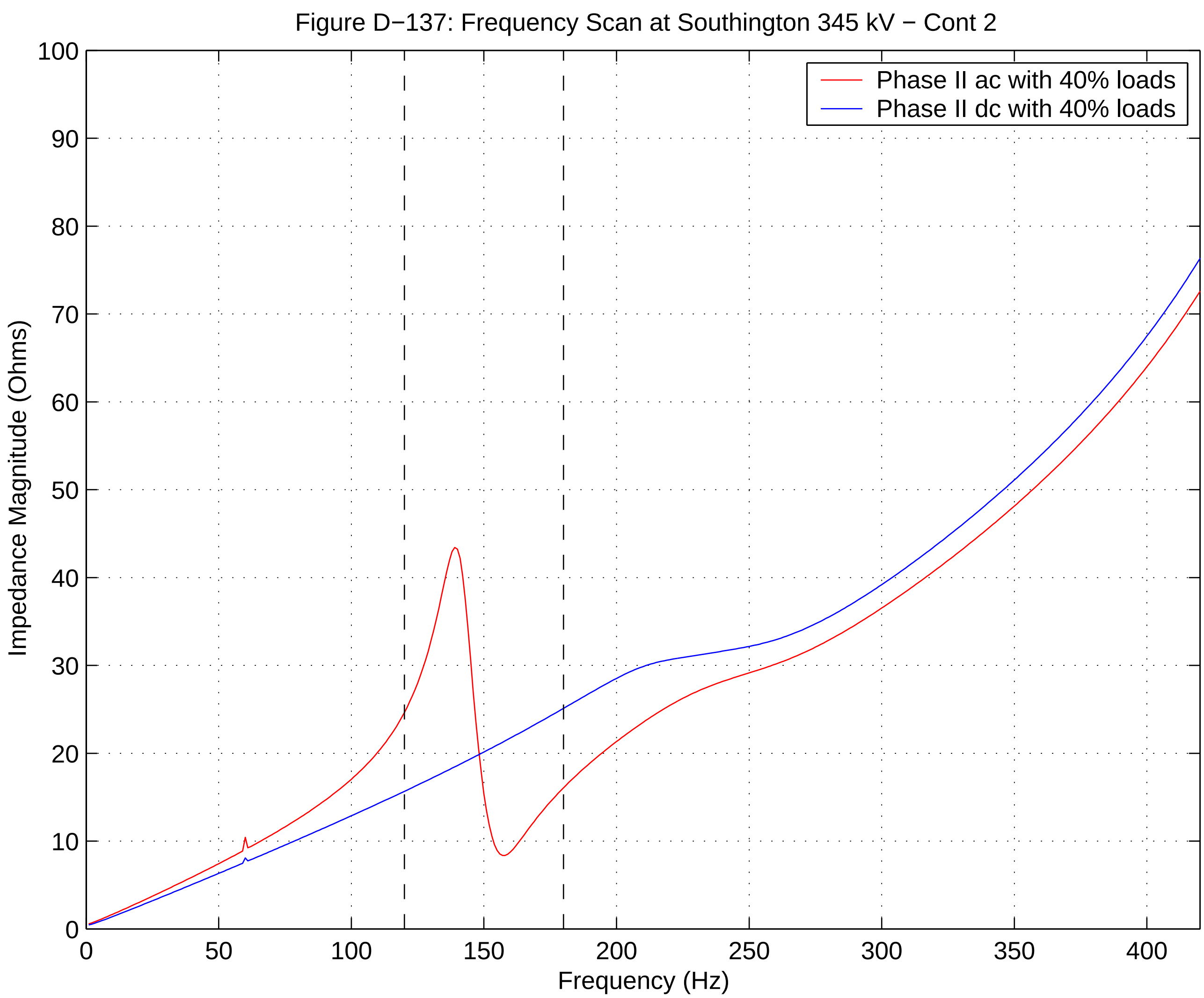


Figure D−137: Frequency Scan at Southington 345 kV − Cont 2
Phase II ac with 40% loads
Phase II dc with 40% loads
Impedance Magnitude (Ohms)
Frequency (Hz)
0
10
20
30
40
50
60
70
80
90
100
0
50
100
150
200
250
300
350
400

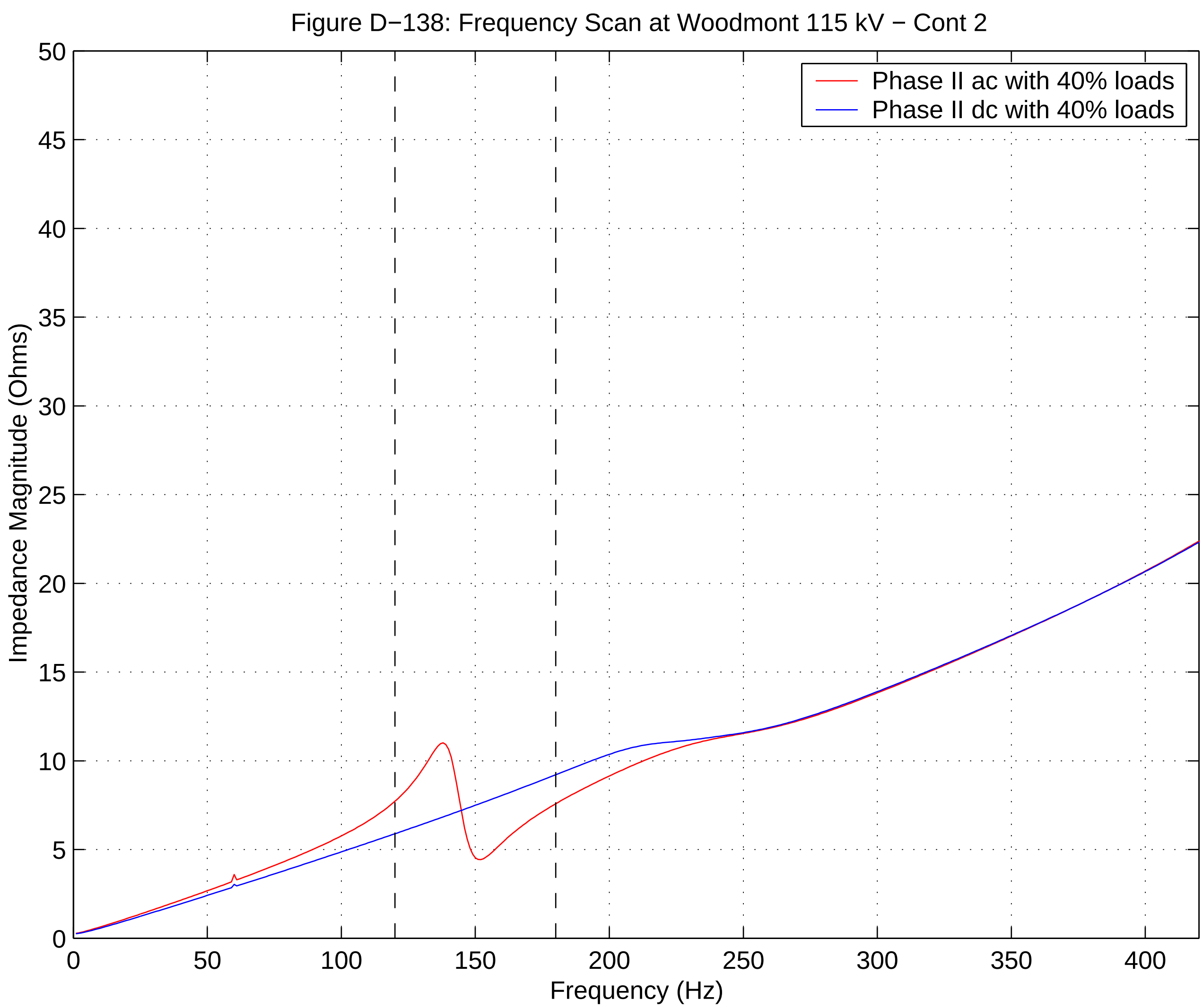


Figure D−138: Frequency Scan at Woodmont 115 kV − Cont 2
Phase II ac with 40% loads
Phase II dc with 40% loads
Impedance Magnitude (Ohms)
Frequency (Hz)
0
5
10
15
20
25
30
35
40
45
50
0
50
100
150
200
250
300
350
400

Figure D−139: Frequency Scan at Norwalk 345 kV

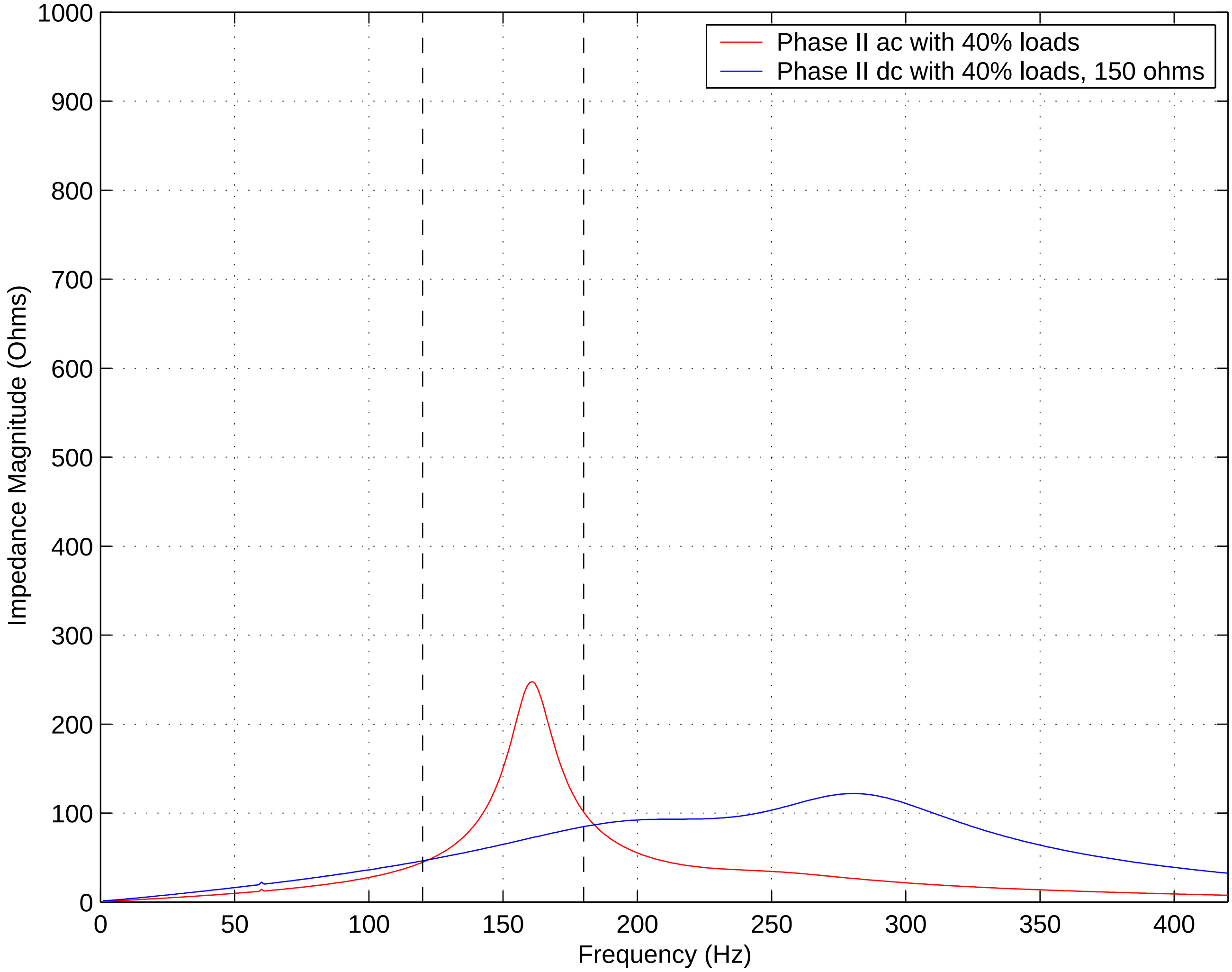


Figure D−140: Frequency Scan at Beseck 345 kV

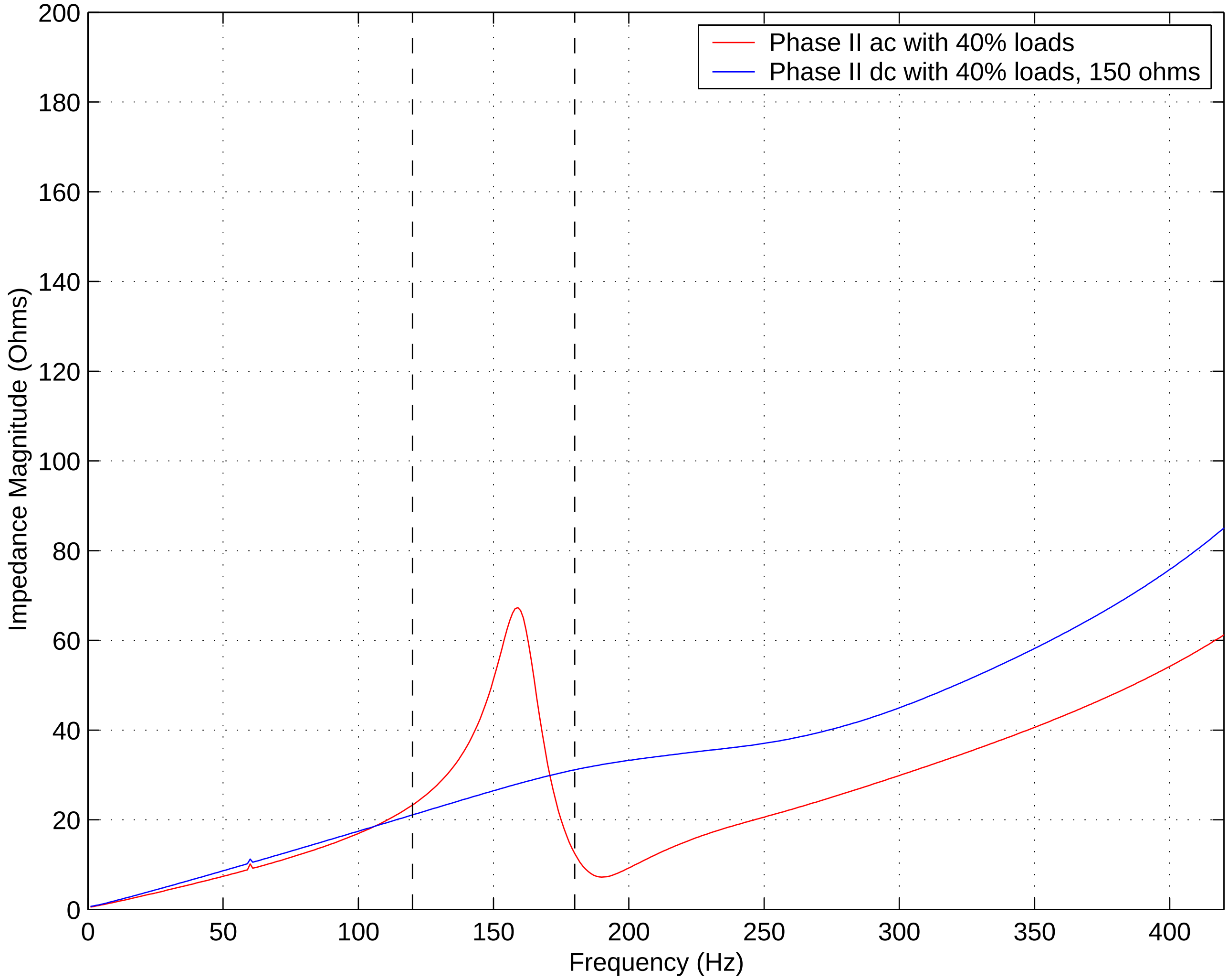
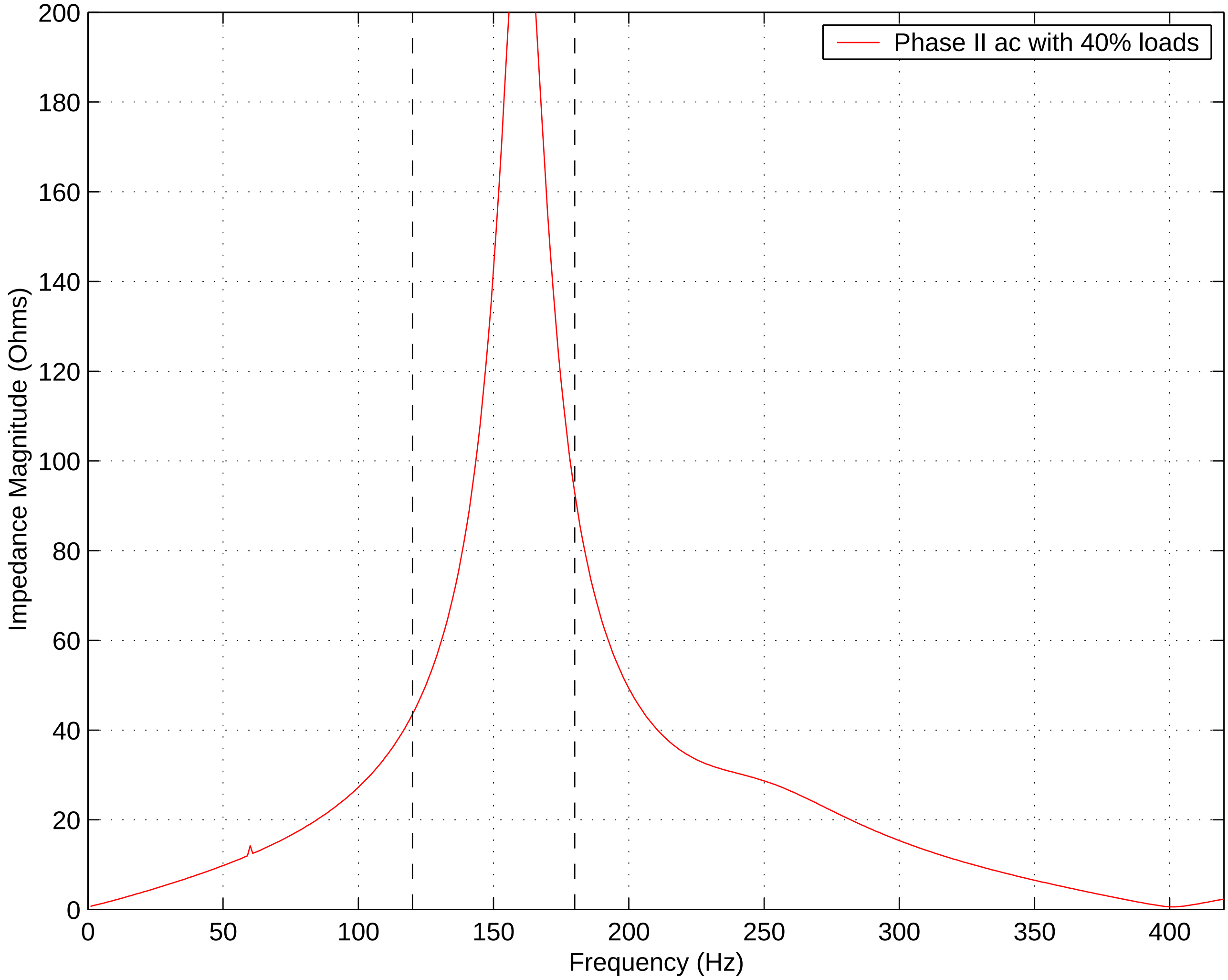


Figure D−141: Frequency Scan at Devon 345 kV



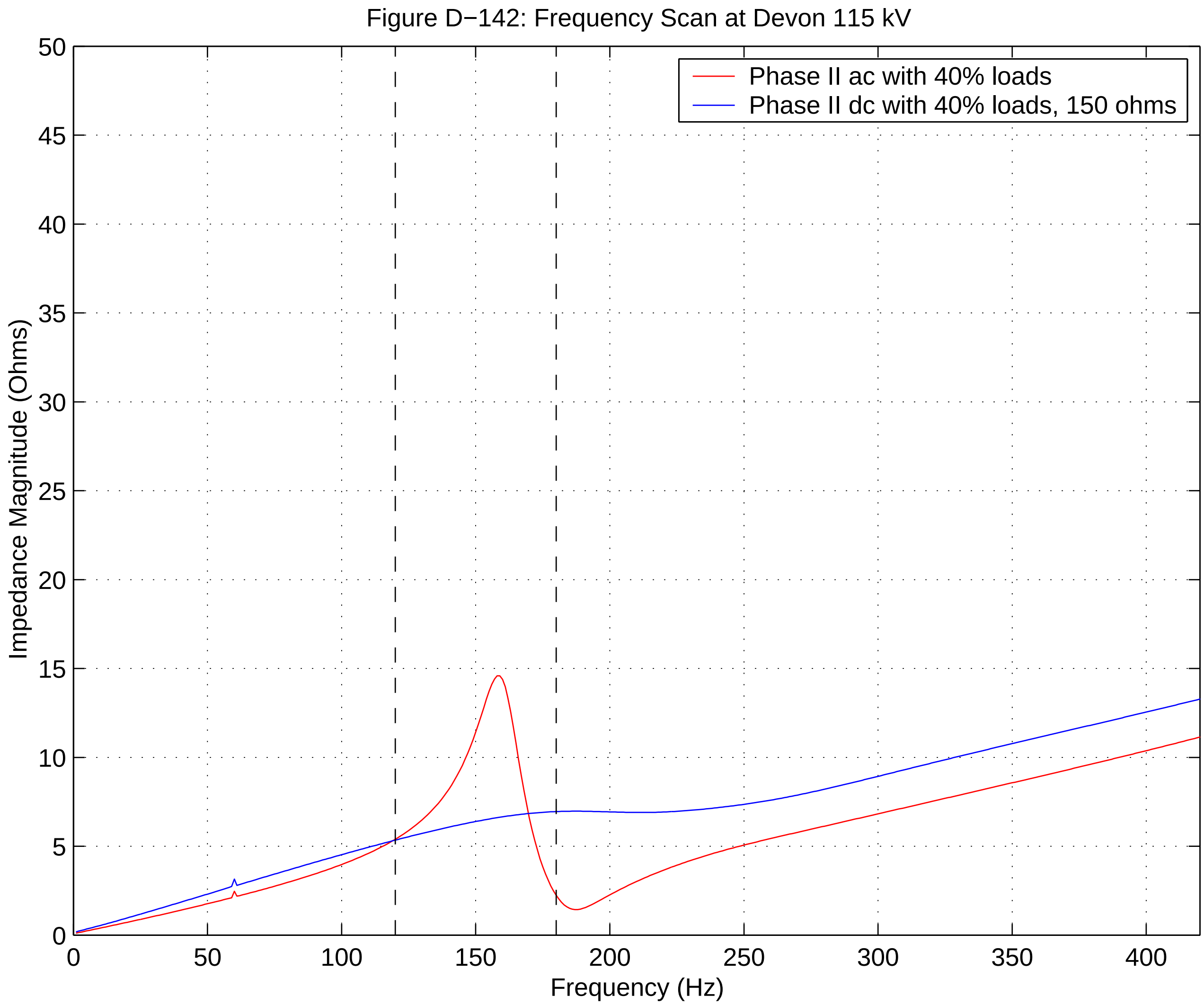


Figure D−142: Frequency Scan at Devon 115 kV
Phase II ac with 40% loads
Phase II dc with 40% loads, 150 ohms
Impedance Magnitude (Ohms)
Frequency (Hz)
0
5
10
15
20
25
30
35
40
45
50
0
50
100
150
200
250
300
350
400

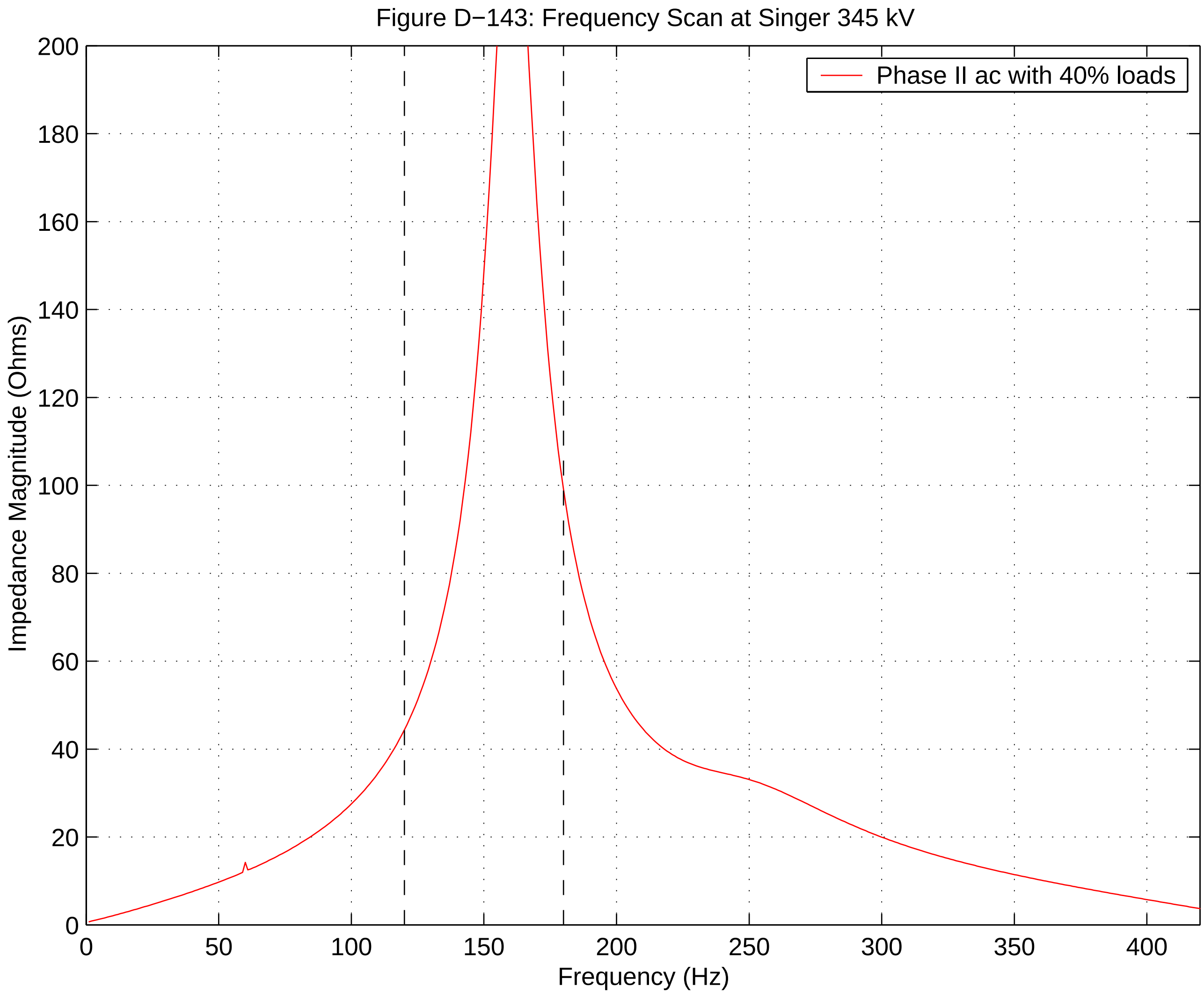


Figure D−143: Frequency Scan at Singer 345 kV
Phase II ac with 40% loads
Impedance Magnitude (Ohms)
Frequency (Hz)
0
20
40
60
80
100
120
140
160
180
200
0
50
100
150
200
250
300
350
400

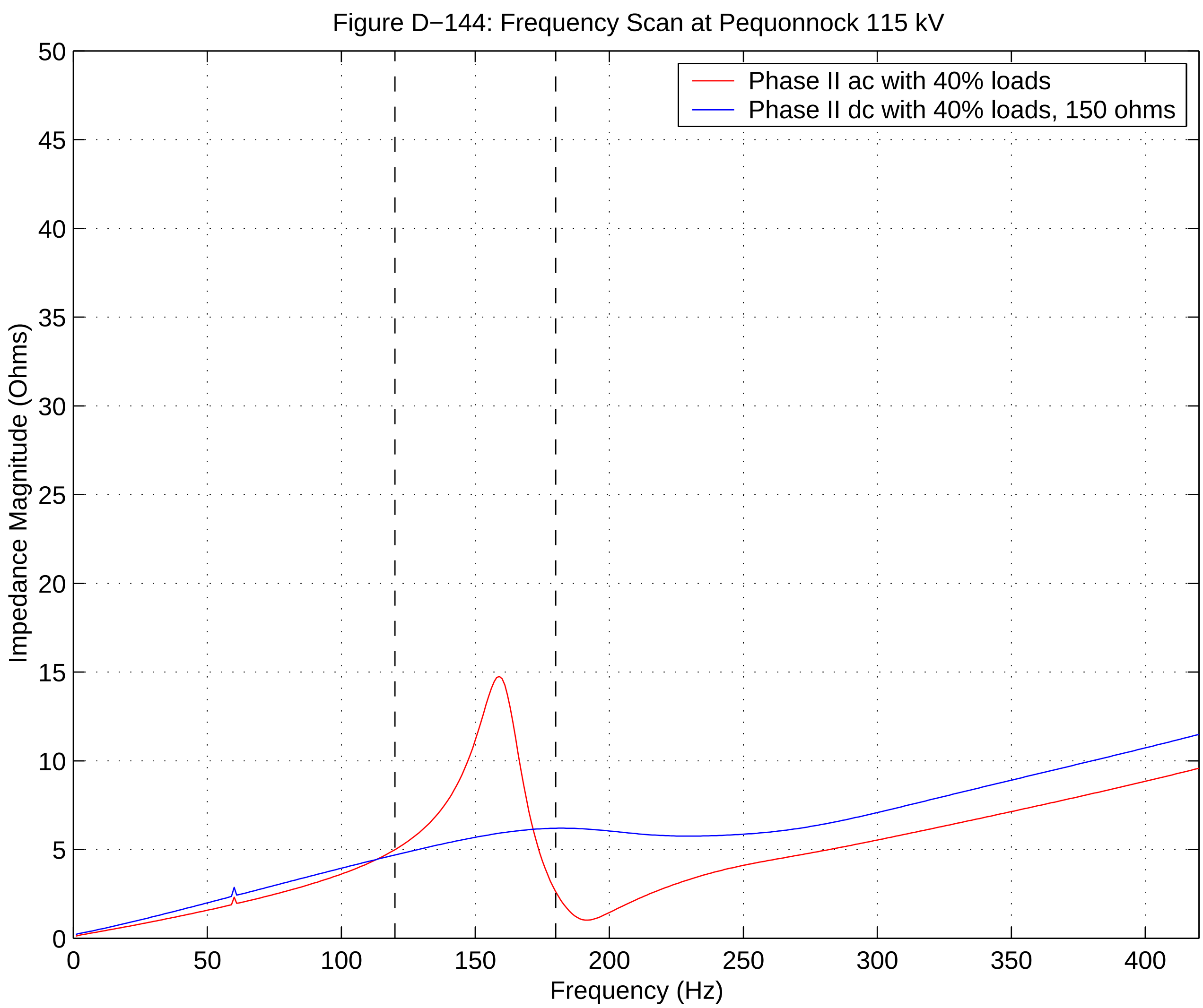


Figure D−144: Frequency Scan at Pequonnock 115 kV
Phase II ac with 40% loads
Phase II dc with 40% loads, 150 ohms
Impedance Magnitude (Ohms)
Frequency (Hz)
0
5
10
15
20
25
30
35
40
45
50
0
50
100
150
200
250
300
350
400

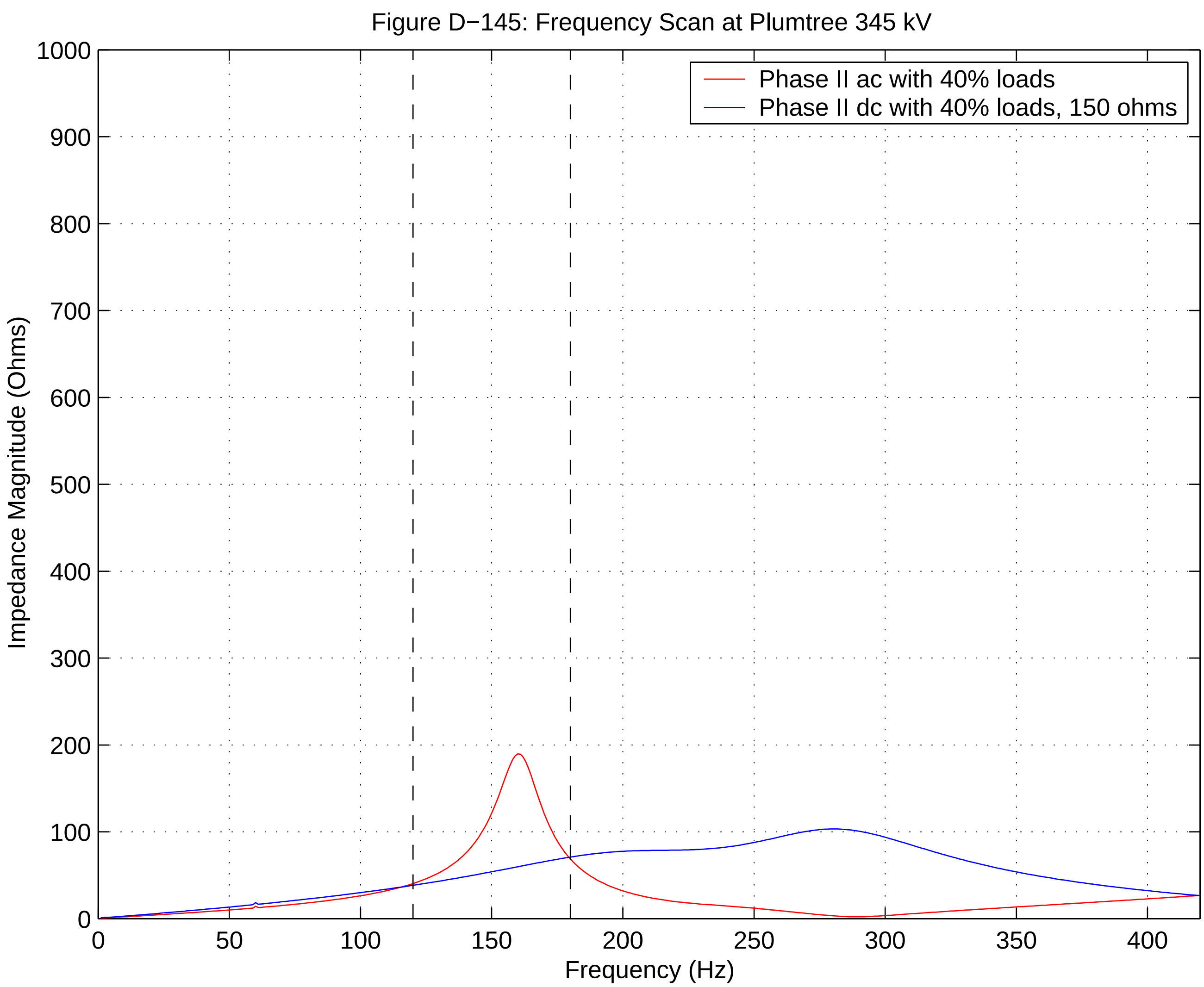


Figure D−145: Frequency Scan at Plumtree 345 kV
Phase II ac with 40% loads
Phase II dc with 40% loads, 150 ohms
Impedance Magnitude (Ohms)
Frequency (Hz)
0
100
200
300
400
500
600
700
800
900
1000
0
50
100
150
200
250
300
350
400

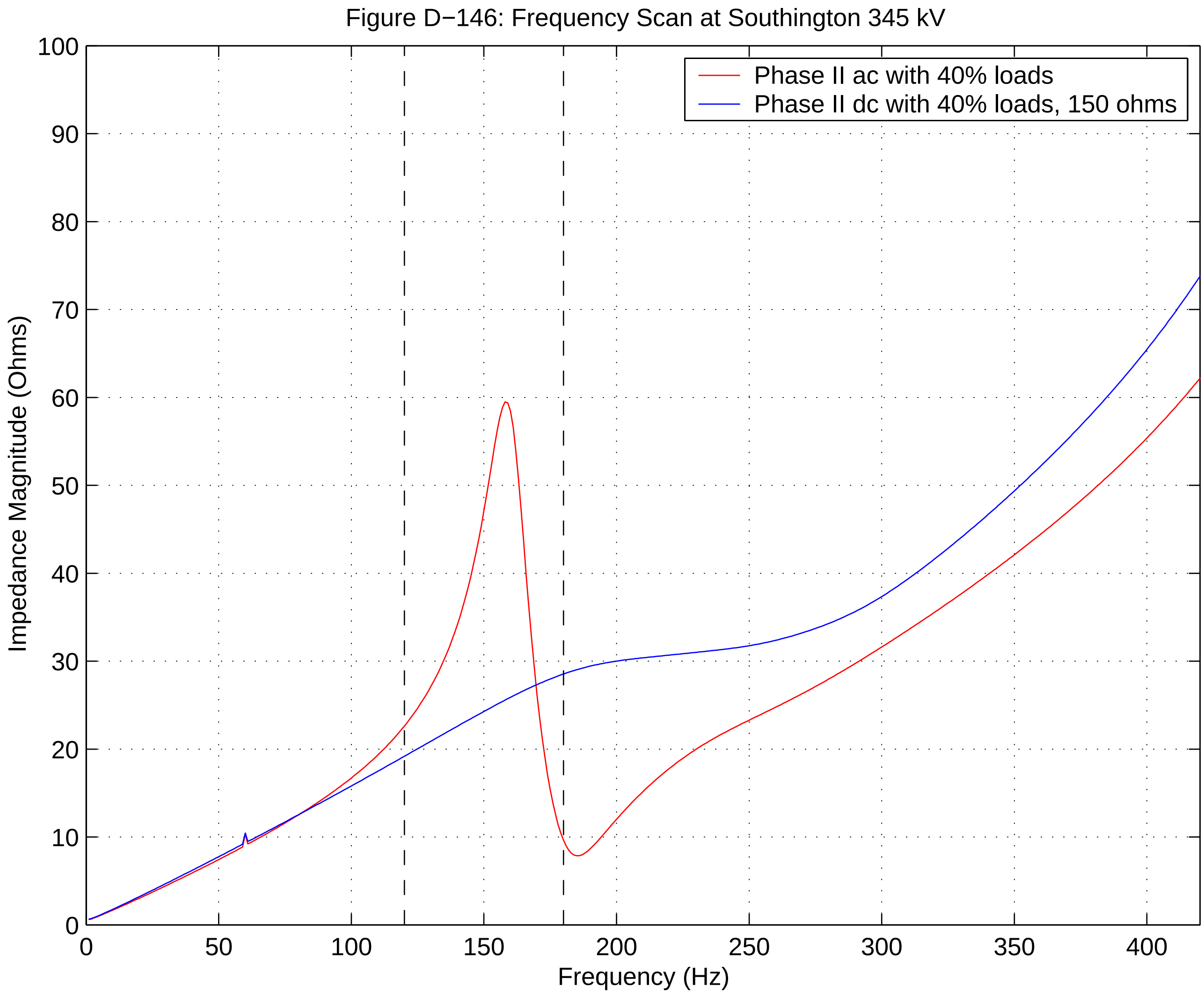


Figure D−146: Frequency Scan at Southington 345 kV
Phase II ac with 40% loads
Phase II dc with 40% loads, 150 ohms
Impedance Magnitude (Ohms)
Frequency (Hz)
0
10
20
30
40
50
60
70
80
90
100
0
50
100
150
200
250
300
350
400

Figure D−147: Frequency Scan at Woodmont 115 kV

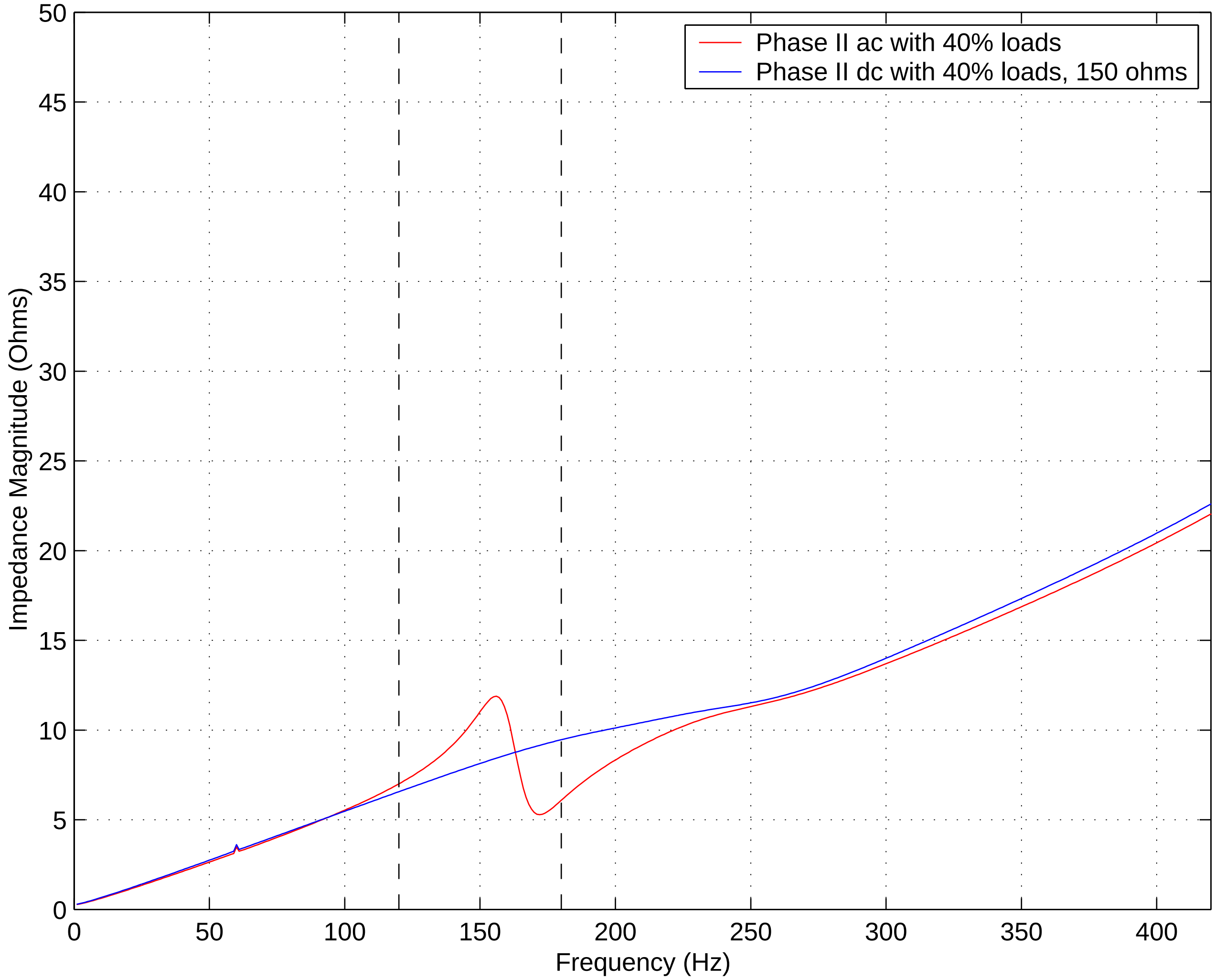
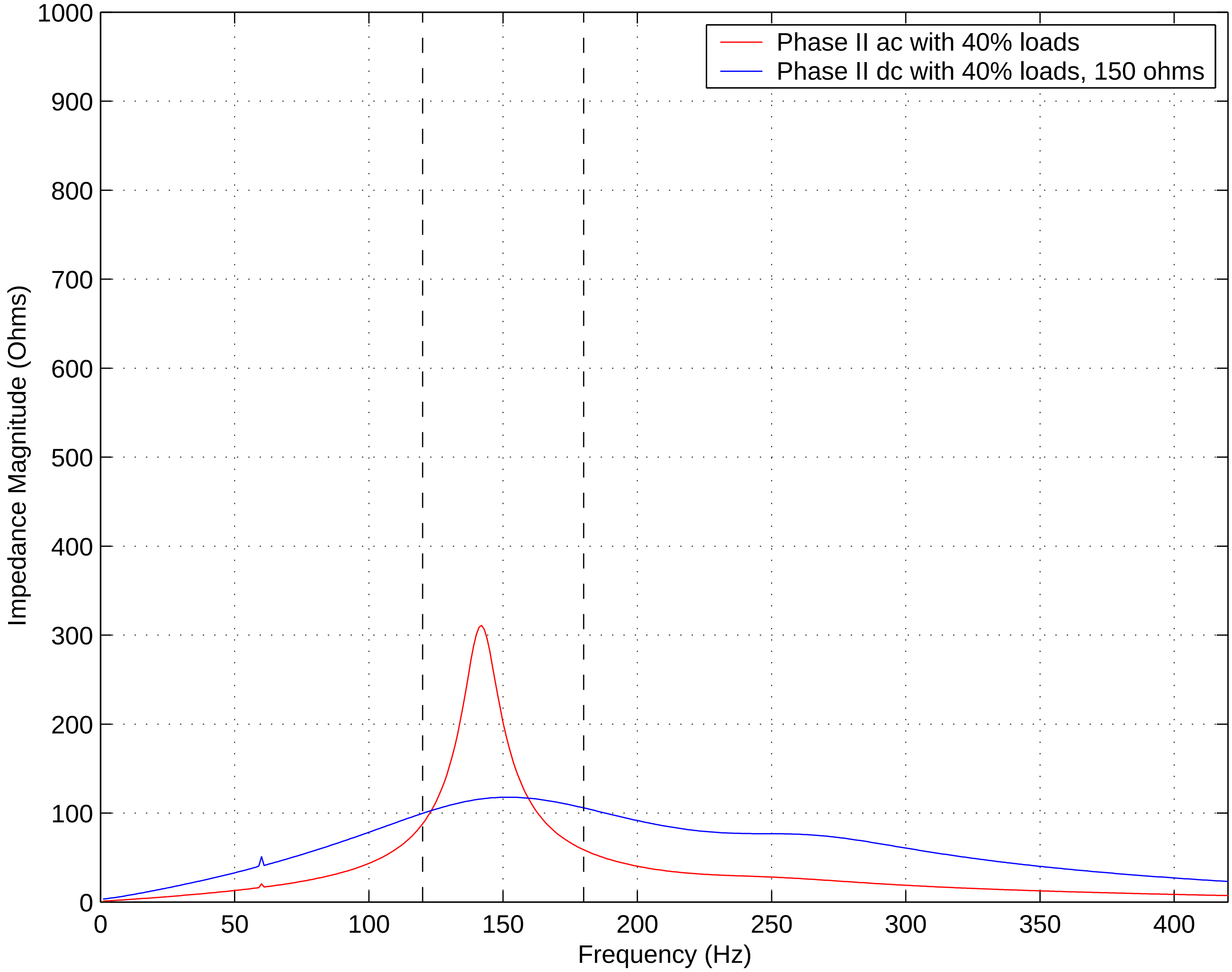


Figure D−148: Frequency Scan at Norwalk 345 kV − Cont 2



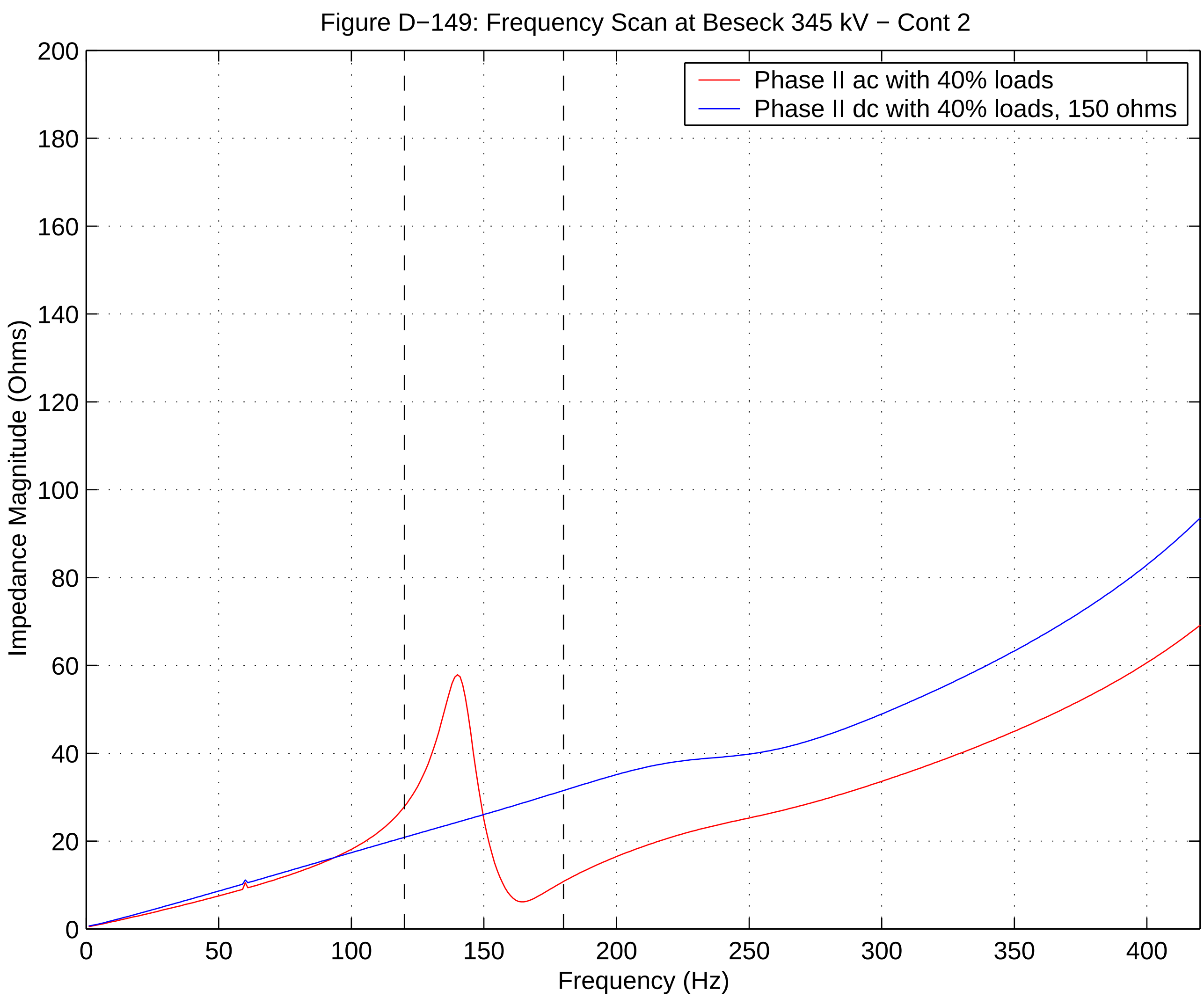


Figure D−149: Frequency Scan at Beseck 345 kV − Cont 2
Phase II ac with 40% loads
Phase II dc with 40% loads, 150 ohms
Impedance Magnitude (Ohms)
Frequency (Hz)
0
20
40
60
80
100
120
140
160
180
200
0
50
100
150
200
250
300
350
400

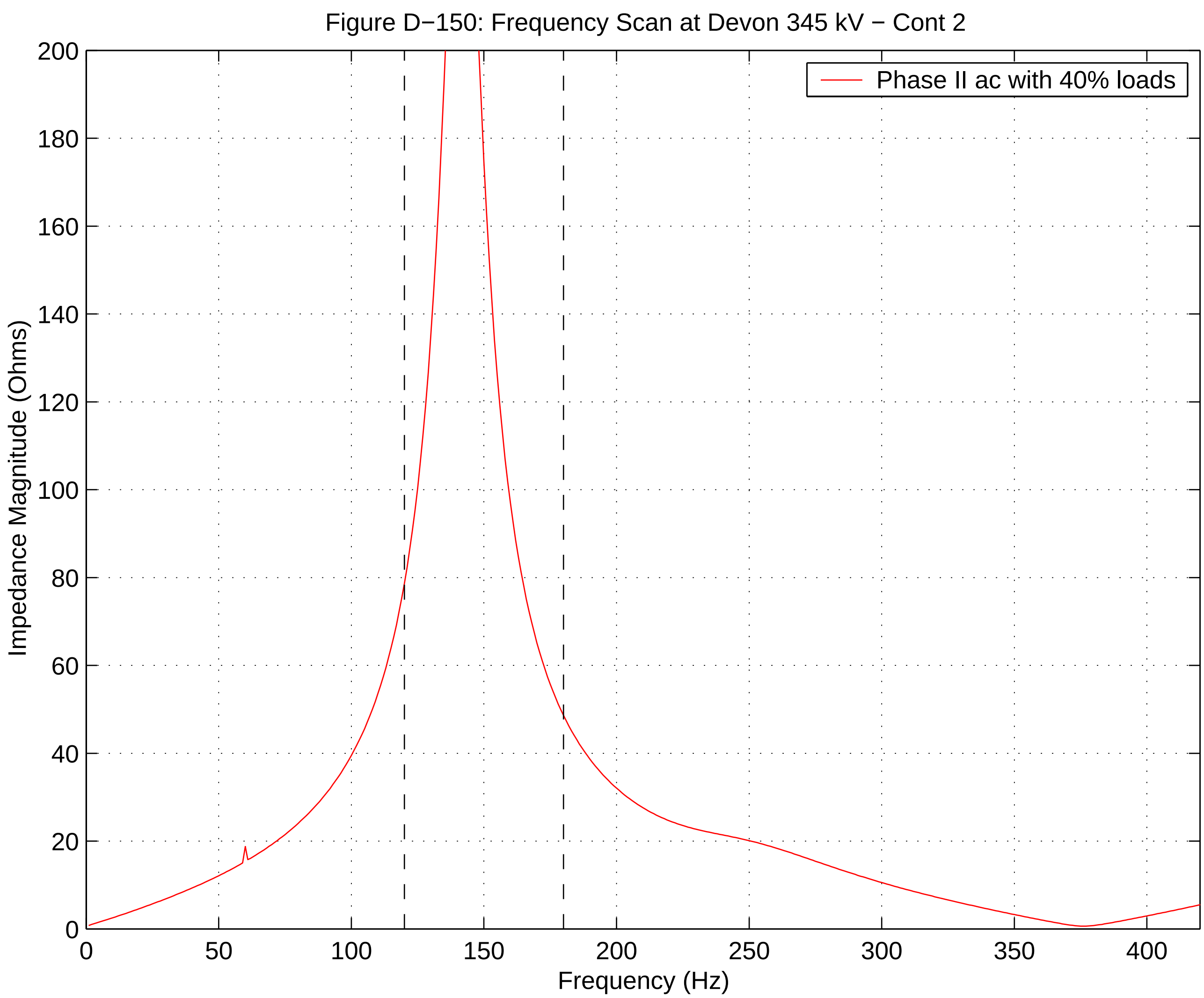


Figure D−150: Frequency Scan at Devon 345 kV − Cont 2
Phase II ac with 40% loads
Impedance Magnitude (Ohms)
Frequency (Hz)
0
20
40
60
80
100
120
140
160
180
200
0
50
100
150
200
250
300
350
400

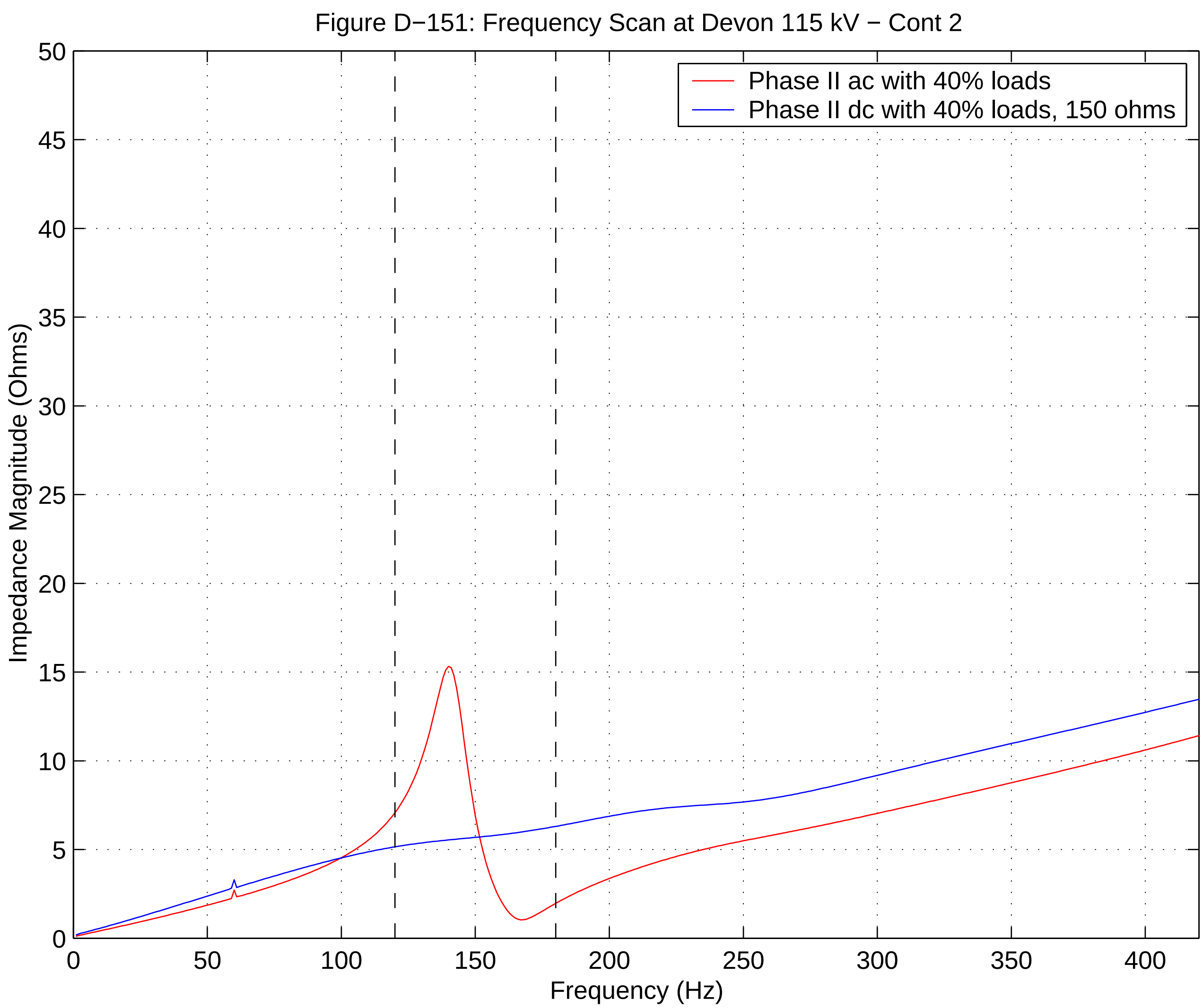


Figure D−151: Frequency Scan at Devon 115 kV − Cont 2
Phase II ac with 40% loads
Phase II dc with 40% loads, 150 ohms
Impedance Magnitude (Ohms)
Frequency (Hz)
0
5
10
15
20
25
30
35
40
45
50
0
50
100
150
200
250
300
350
400

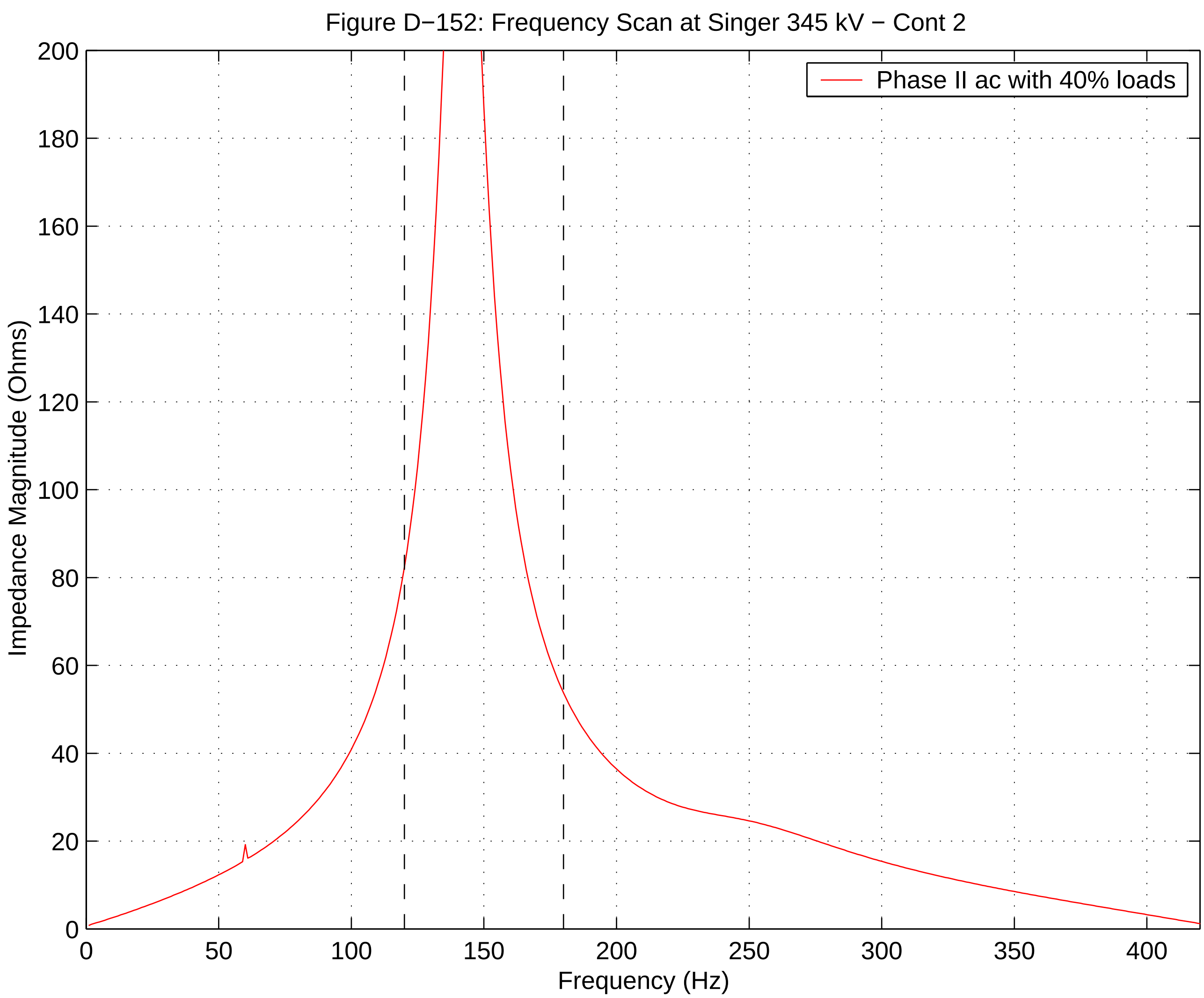


Figure D−152: Frequency Scan at Singer 345 kV − Cont 2
Phase II ac with 40% loads
Impedance Magnitude (Ohms)
Frequency (Hz)
0
20
40
60
80
100
120
140
160
180
200
0
50
100
150
200
250
300
350
400

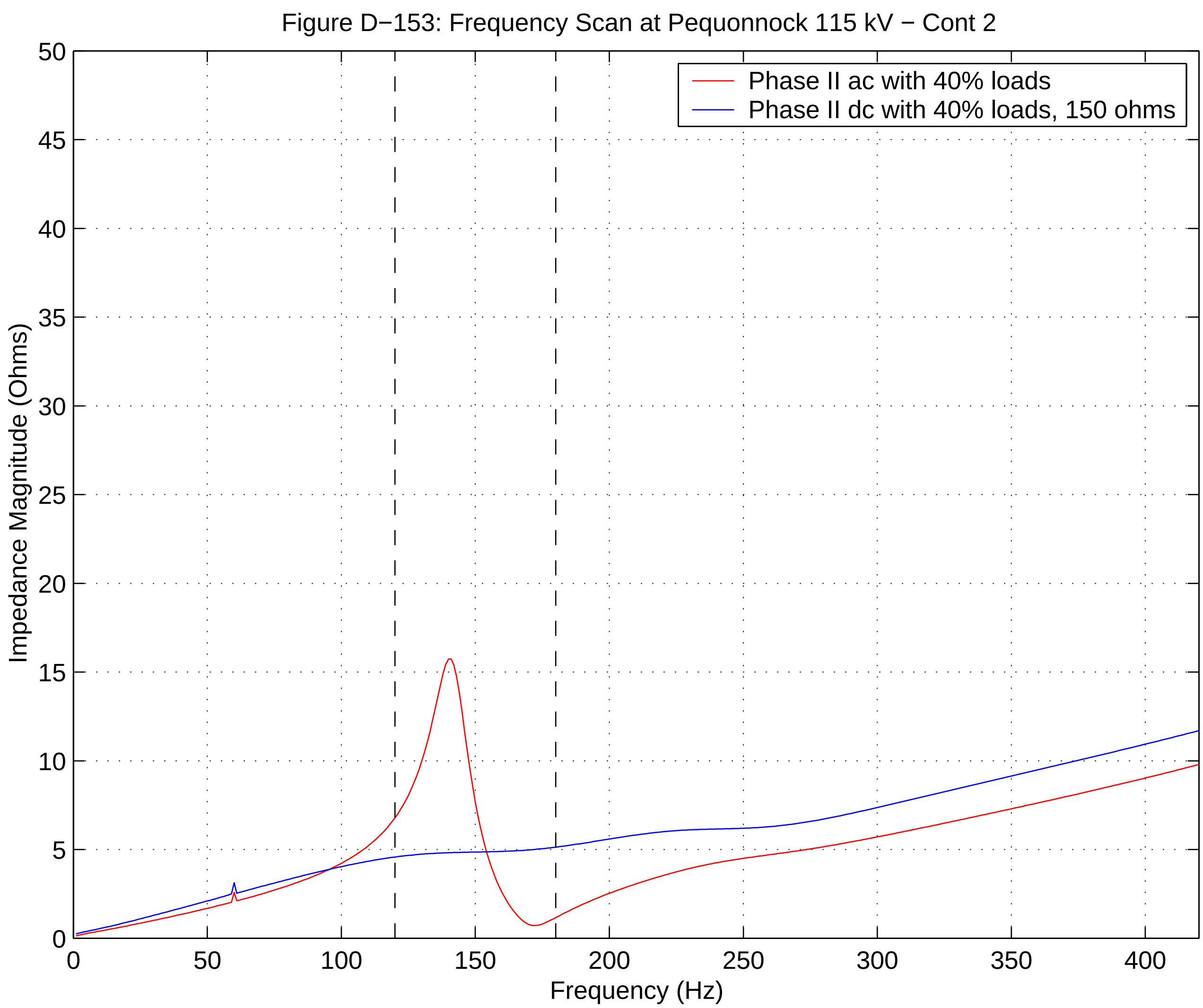


Figure D−153: Frequency Scan at Pequonnock 115 kV − Cont 2
Phase II ac with 40% loads
Phase II dc with 40% loads, 150 ohms
Impedance Magnitude (Ohms)
Frequency (Hz)
0
5
10
15
20
25
30
35
40
45
50
0
50
100
150
200
250
300
350
400

Figure D−154: Frequency Scan at Plumtree 345 kV − Cont 2

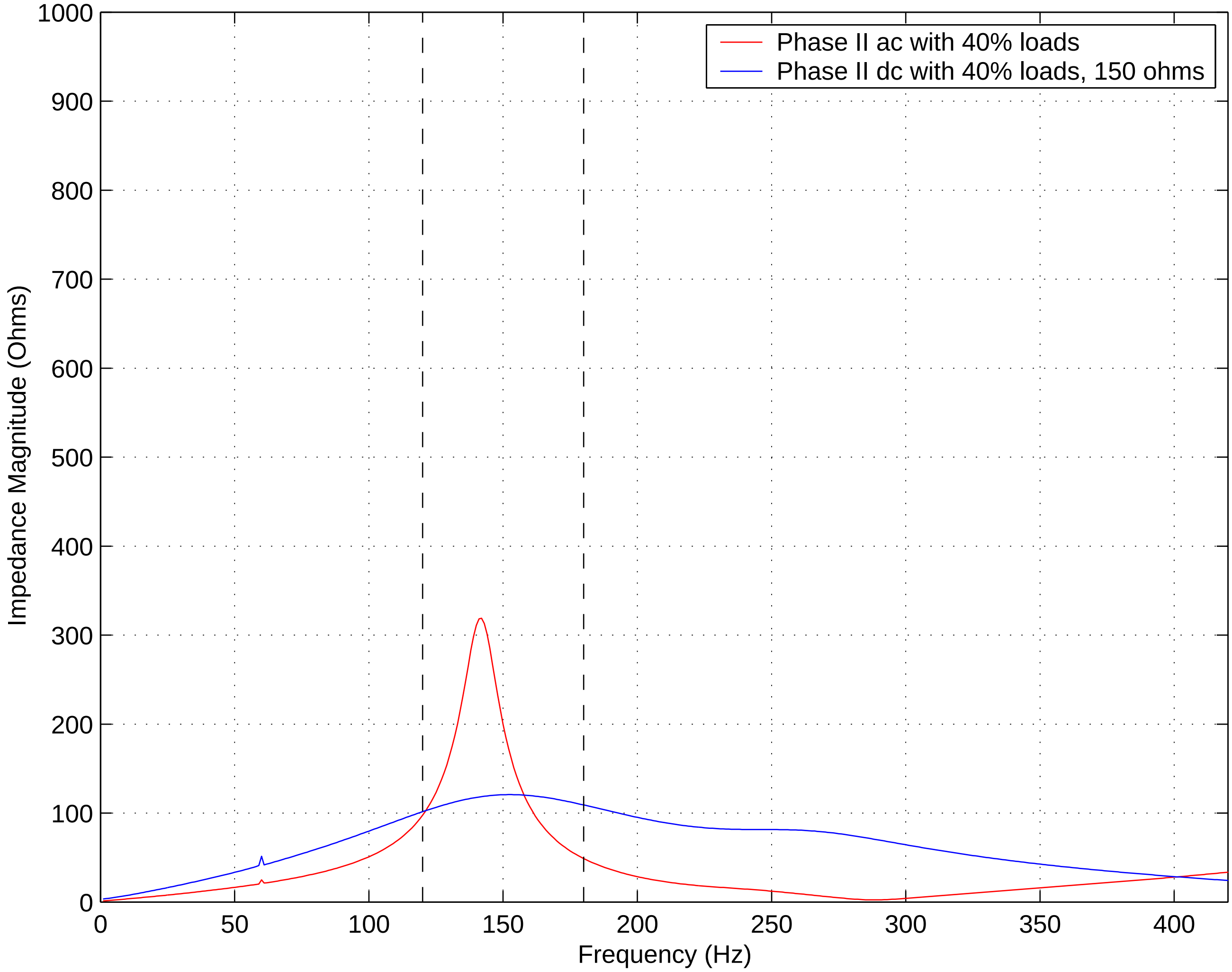
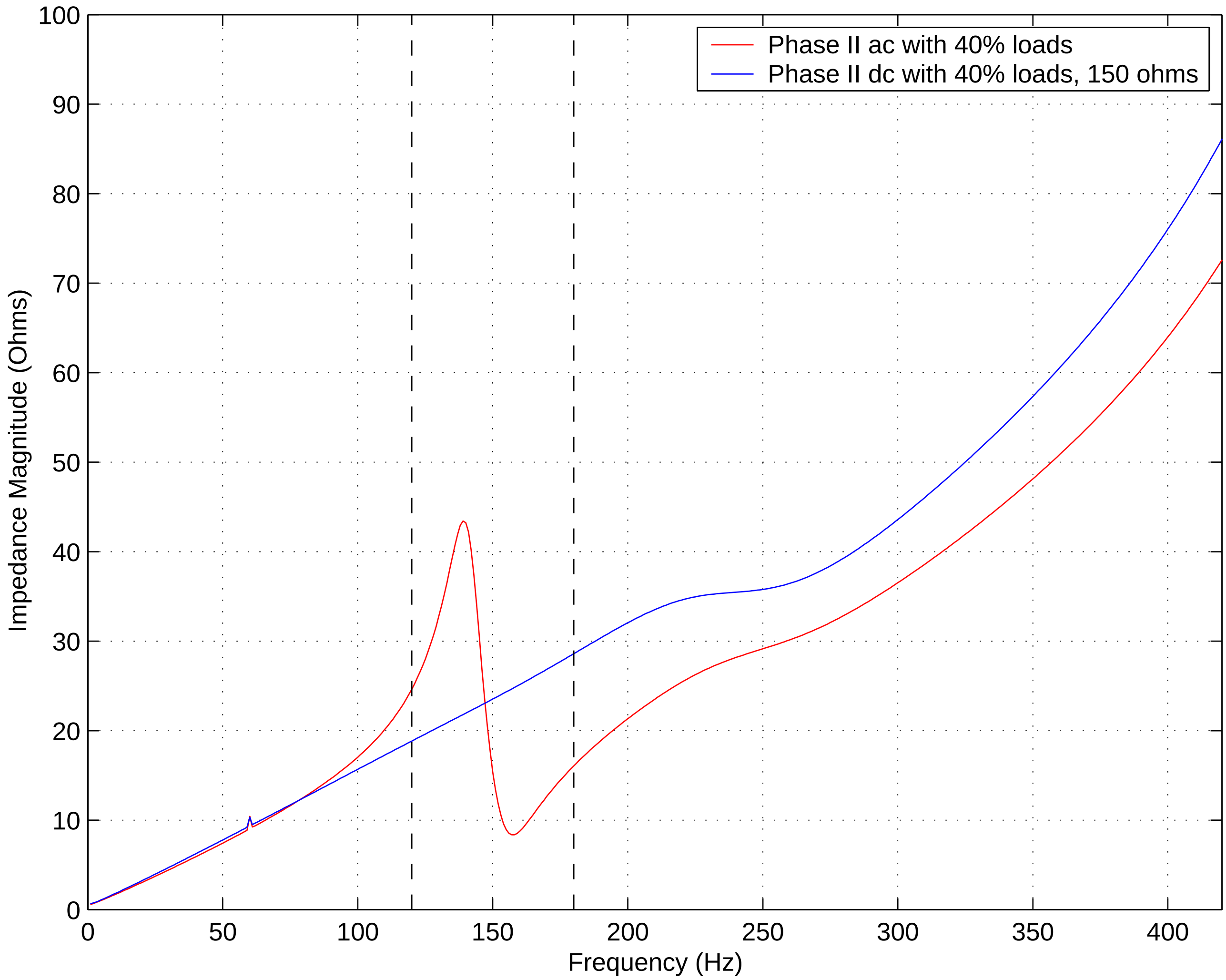


Figure D−155: Frequency Scan at Southington 345 kV − Cont 2



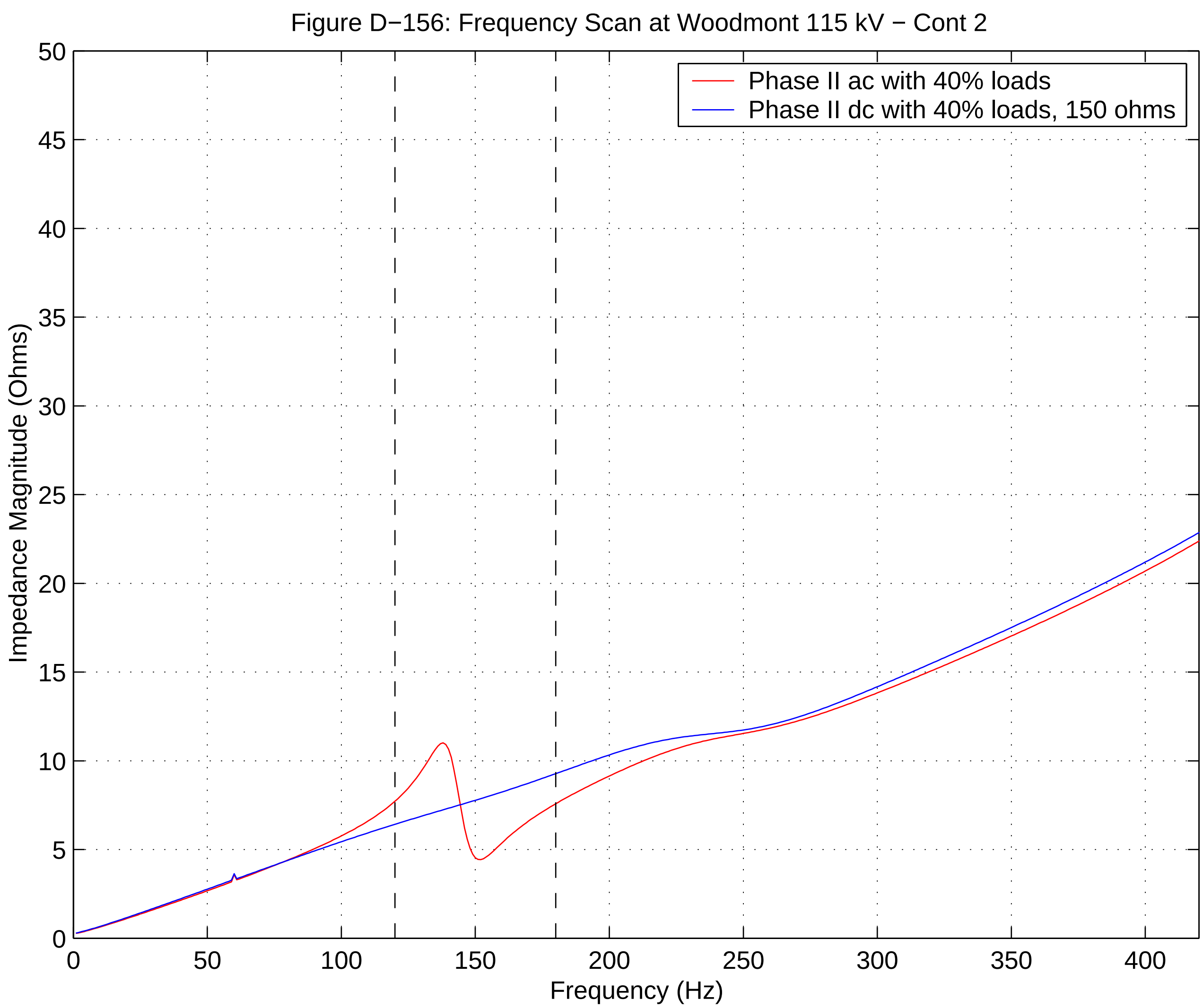


Figure D−156: Frequency Scan at Woodmont 115 kV − Cont 2
Phase II ac with 40% loads
Phase II dc with 40% loads, 150 ohms
Impedance Magnitude (Ohms)
Frequency (Hz)
0
5
10
15
20
25
30
35
40
45
50
0
50
100
150
200
250
300
350
400

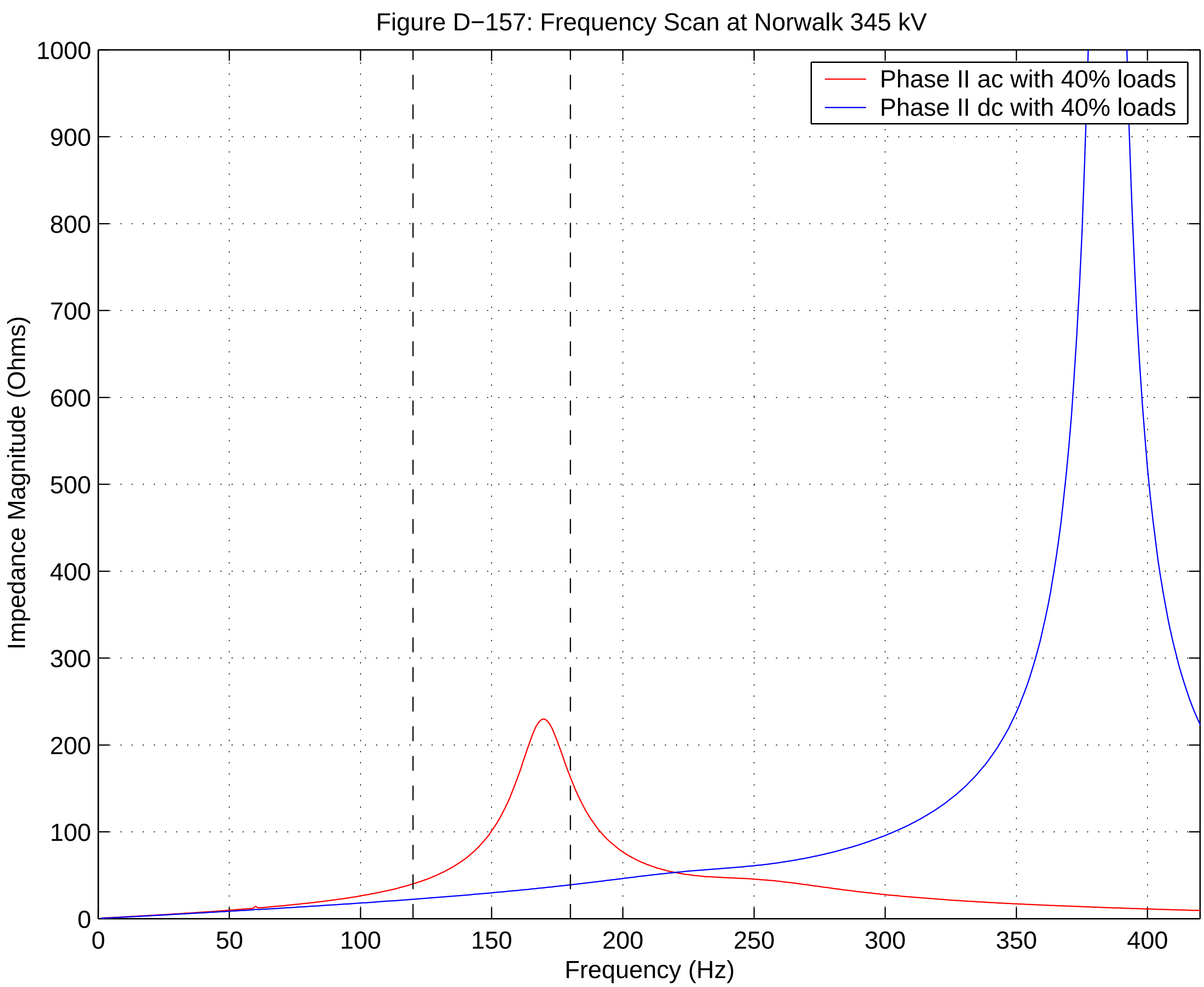
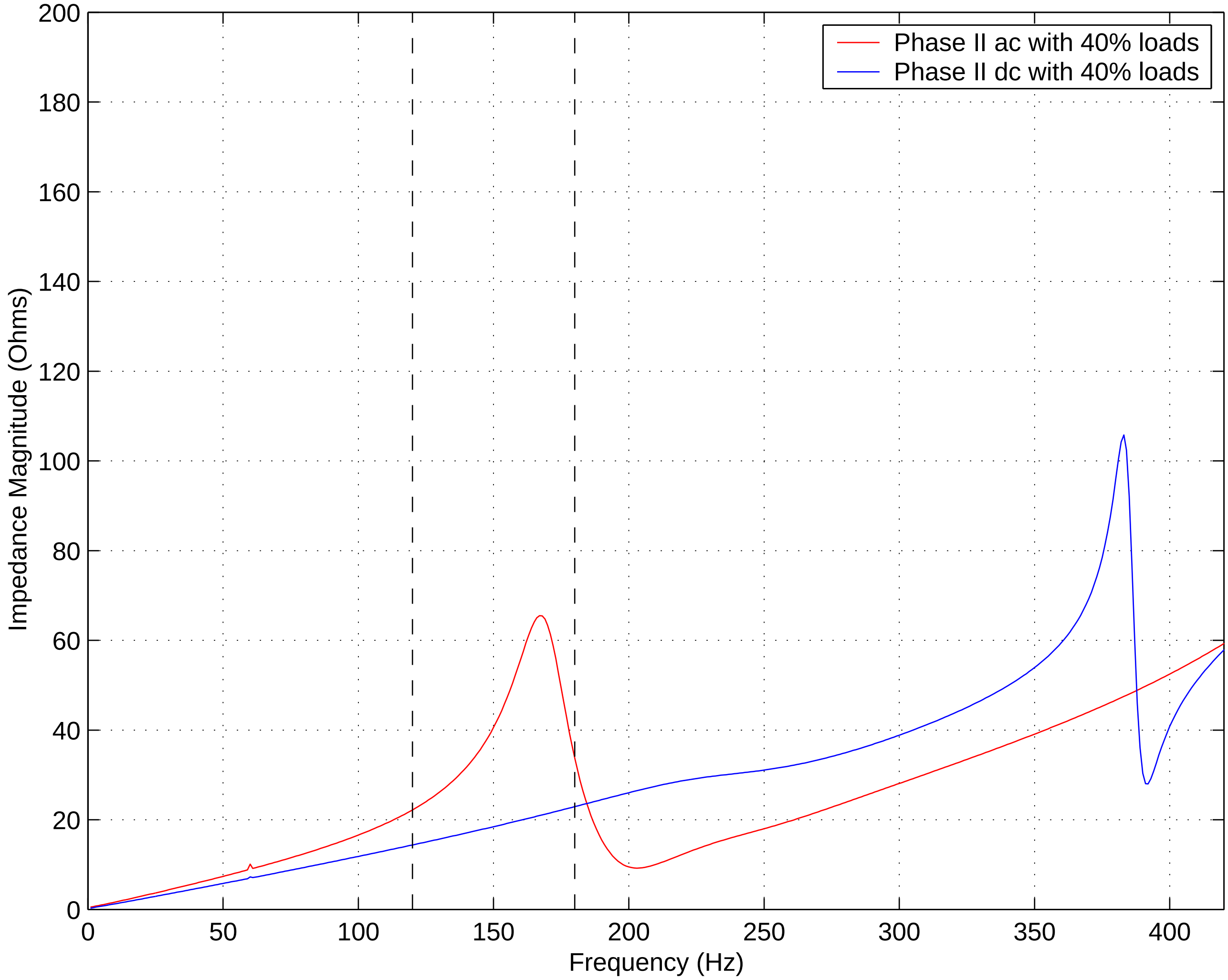


Figure D−157: Frequency Scan at Norwalk 345 kV
Phase II ac with 40% loads
Phase II dc with 40% loads
Impedance Magnitude (Ohms)
Frequency (Hz)
0
100
200
300
400
500
600
700
800
900
1000
0
50
100
150
200
250
300
350
400

Figure D−158: Frequency Scan at Beseck 345 kV



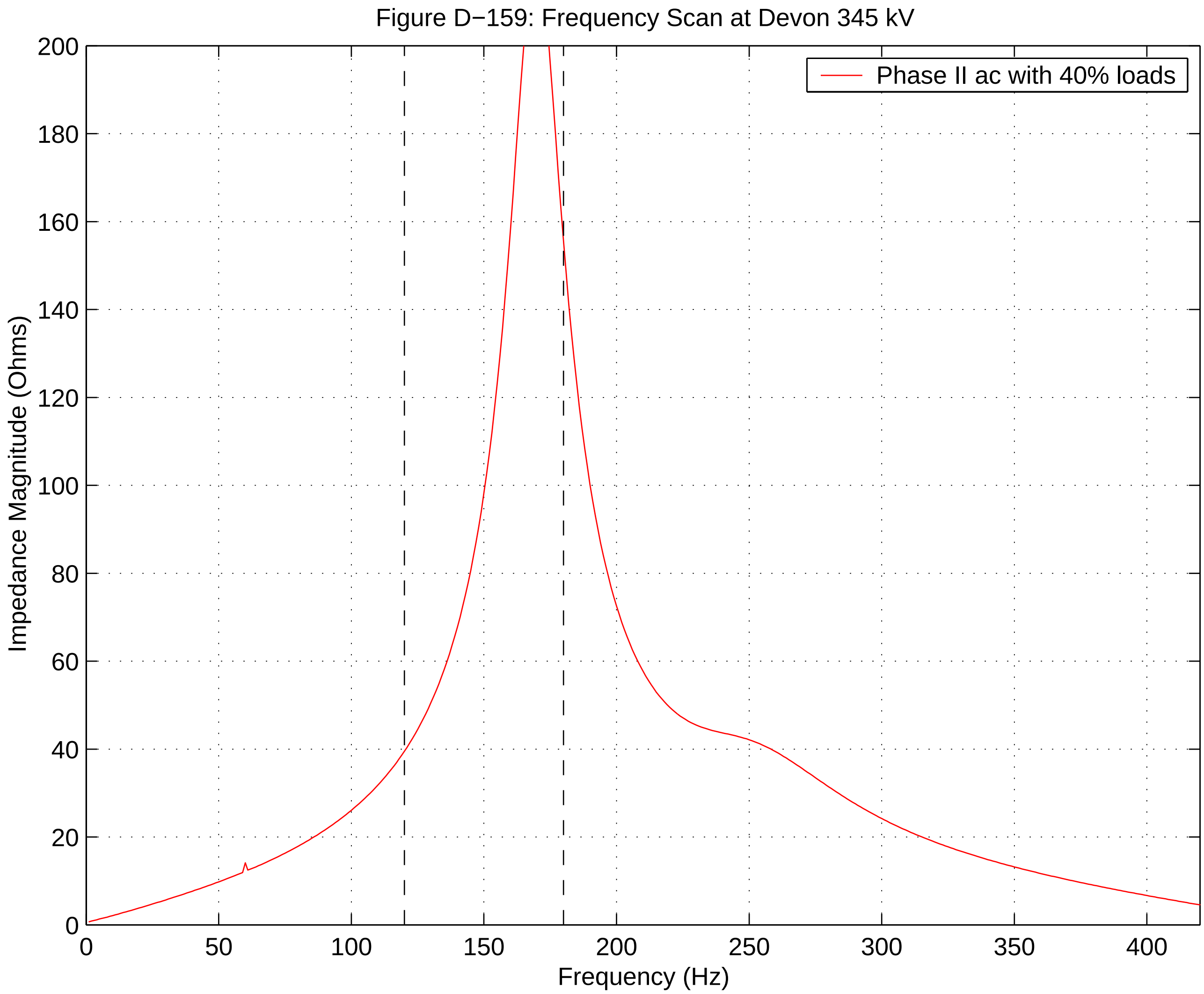


Figure D−159: Frequency Scan at Devon 345 kV
Phase II ac with 40% loads
Impedance Magnitude (Ohms)
Frequency (Hz)
0
20
40
60
80
100
120
140
160
180
200
0
50
100
150
200
250
300
350
400

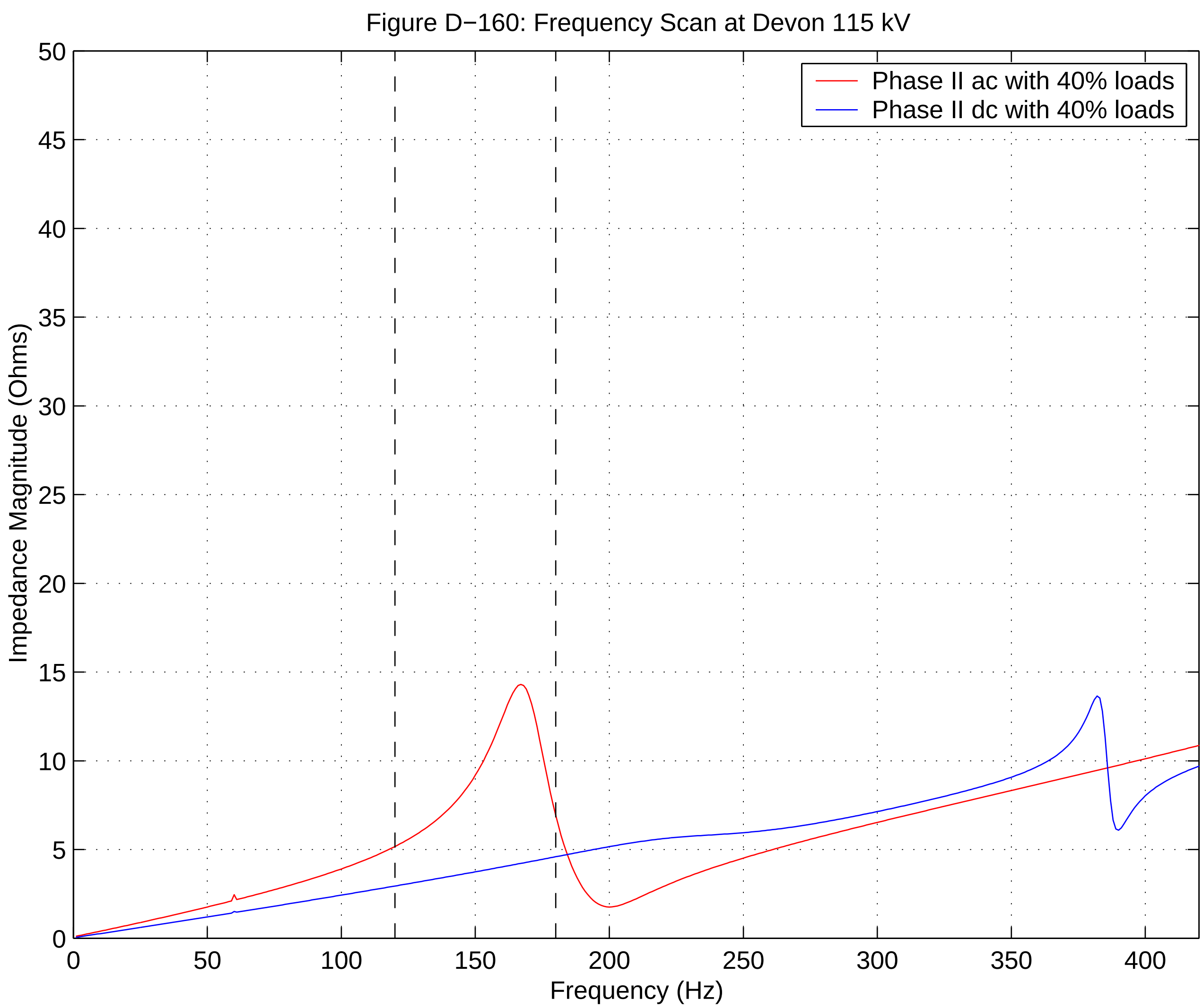


Figure D−160: Frequency Scan at Devon 115 kV
Phase II ac with 40% loads
Phase II dc with 40% loads
Impedance Magnitude (Ohms)
Frequency (Hz)
0
5
10
15
20
25
30
35
40
45
50
0
50
100
150
200
250
300
350
400

Figure D−161: Frequency Scan at Singer 345 kV

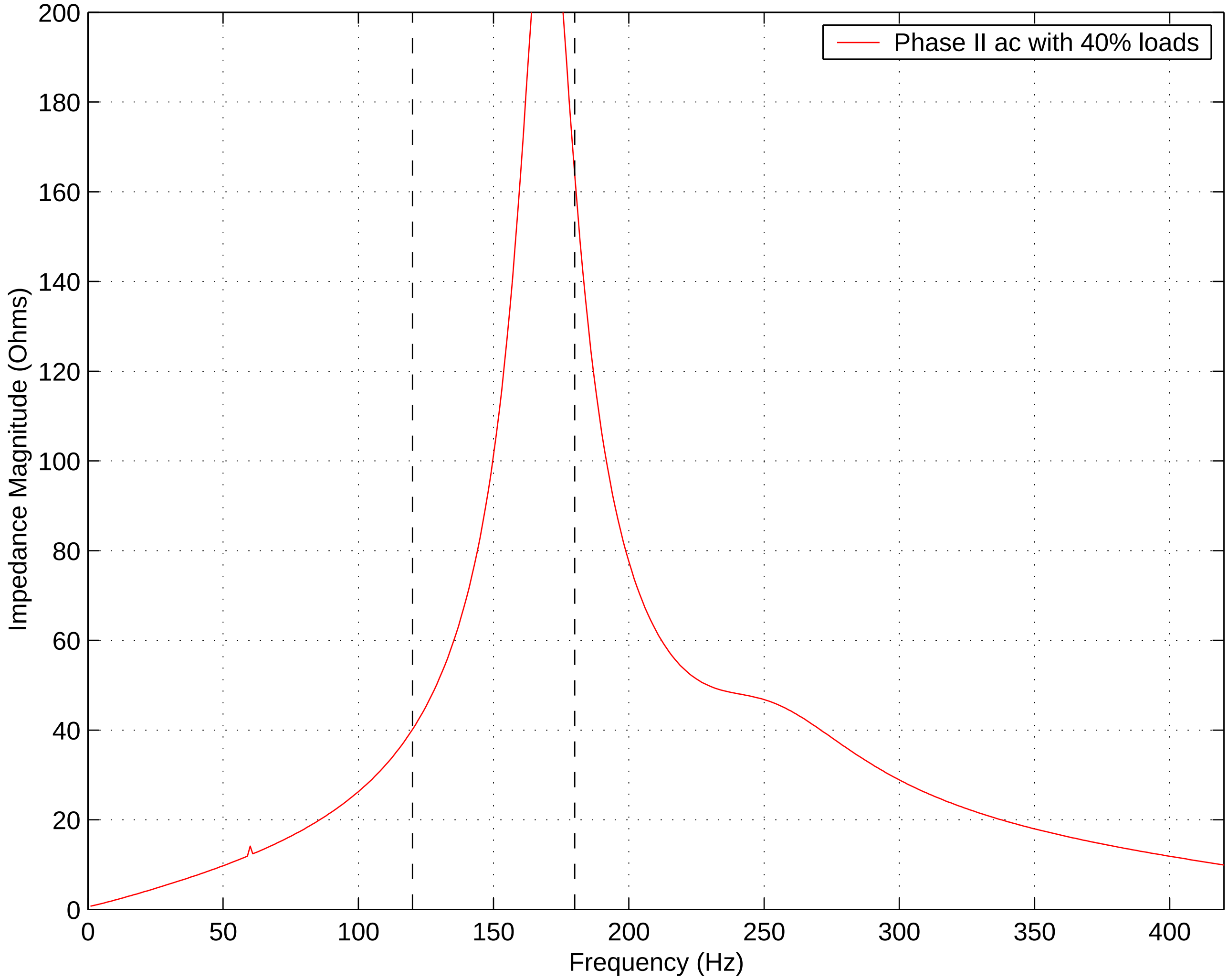
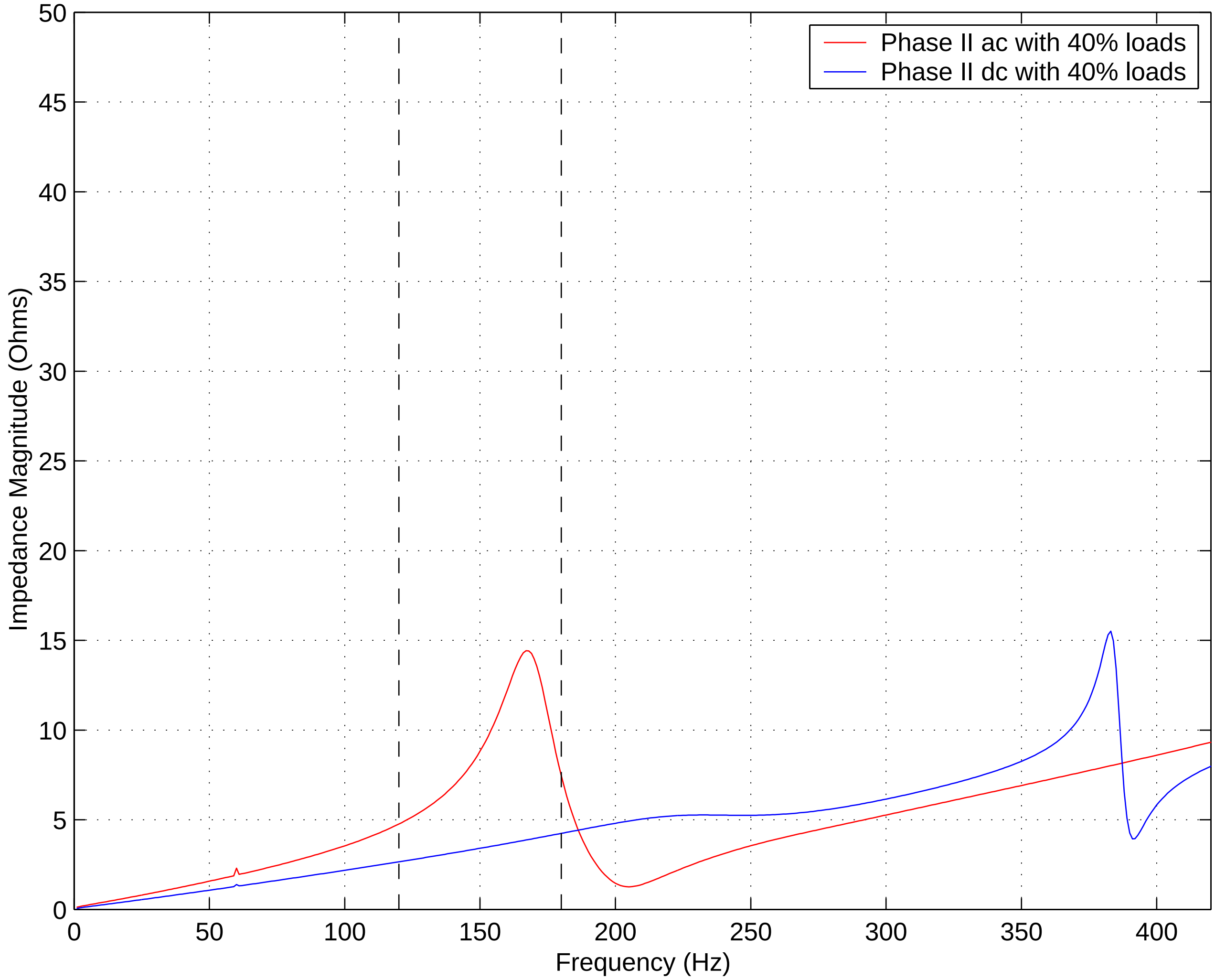


Figure D−162: Frequency Scan at Pequonnock 115 kV



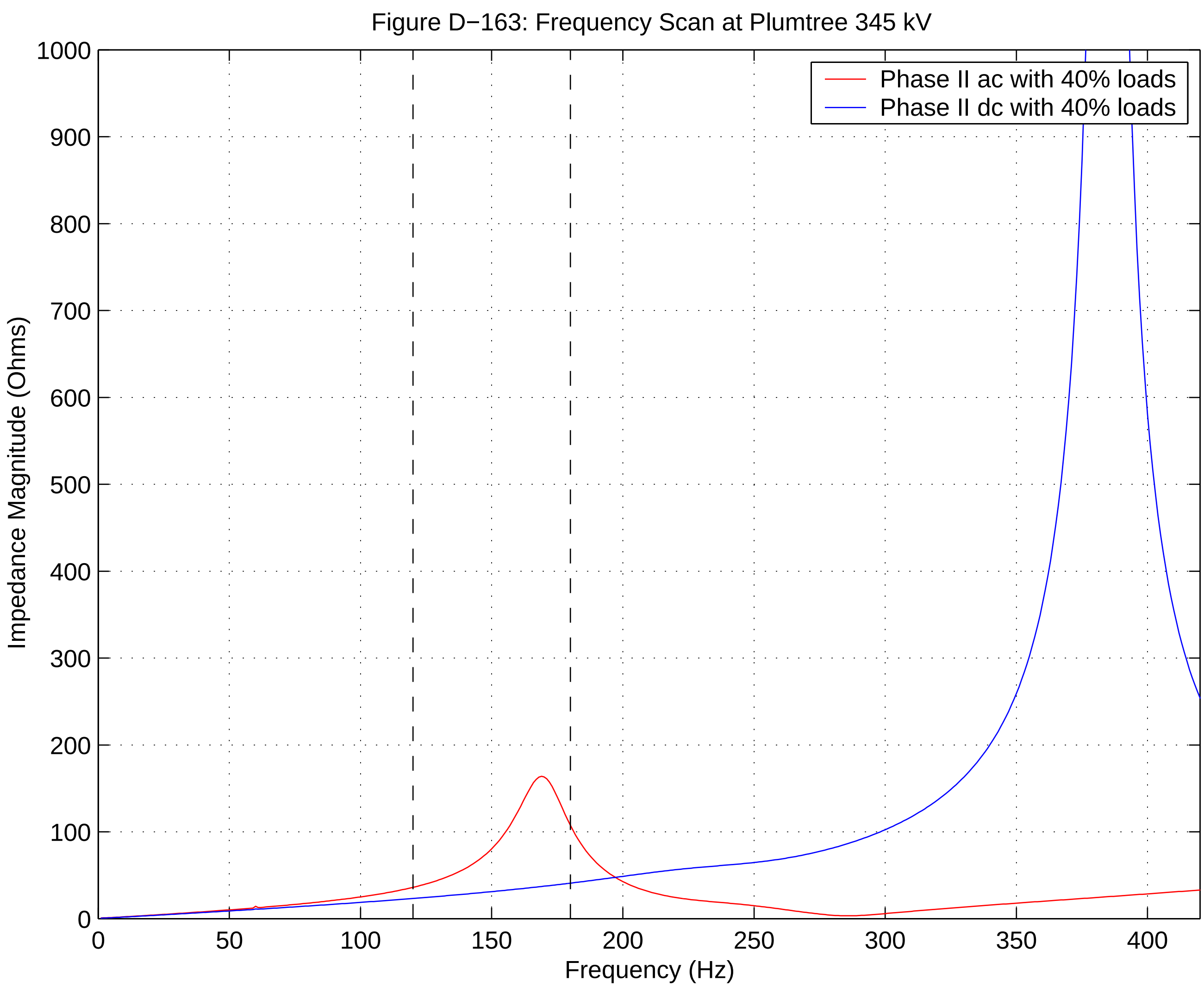


Figure D−163: Frequency Scan at Plumtree 345 kV
Phase II ac with 40% loads
Phase II dc with 40% loads
Impedance Magnitude (Ohms)
Frequency (Hz)
0
100
200
300
400
500
600
700
800
900
1000
0
50
100
150
200
250
300
350
400

Figure D−164: Frequency Scan at Southington 345 kV

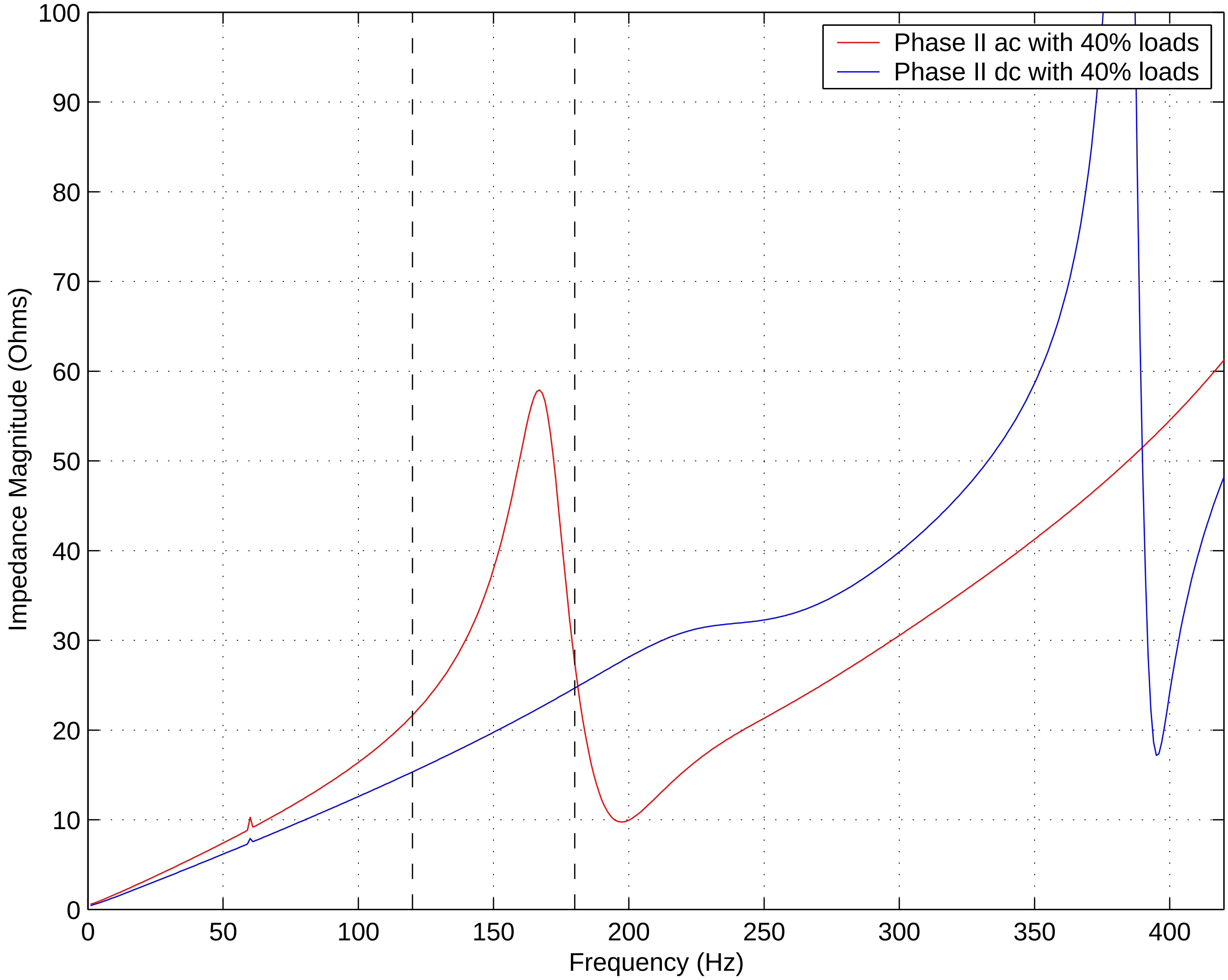


Figure D−165: Frequency Scan at Woodmont 115 kV

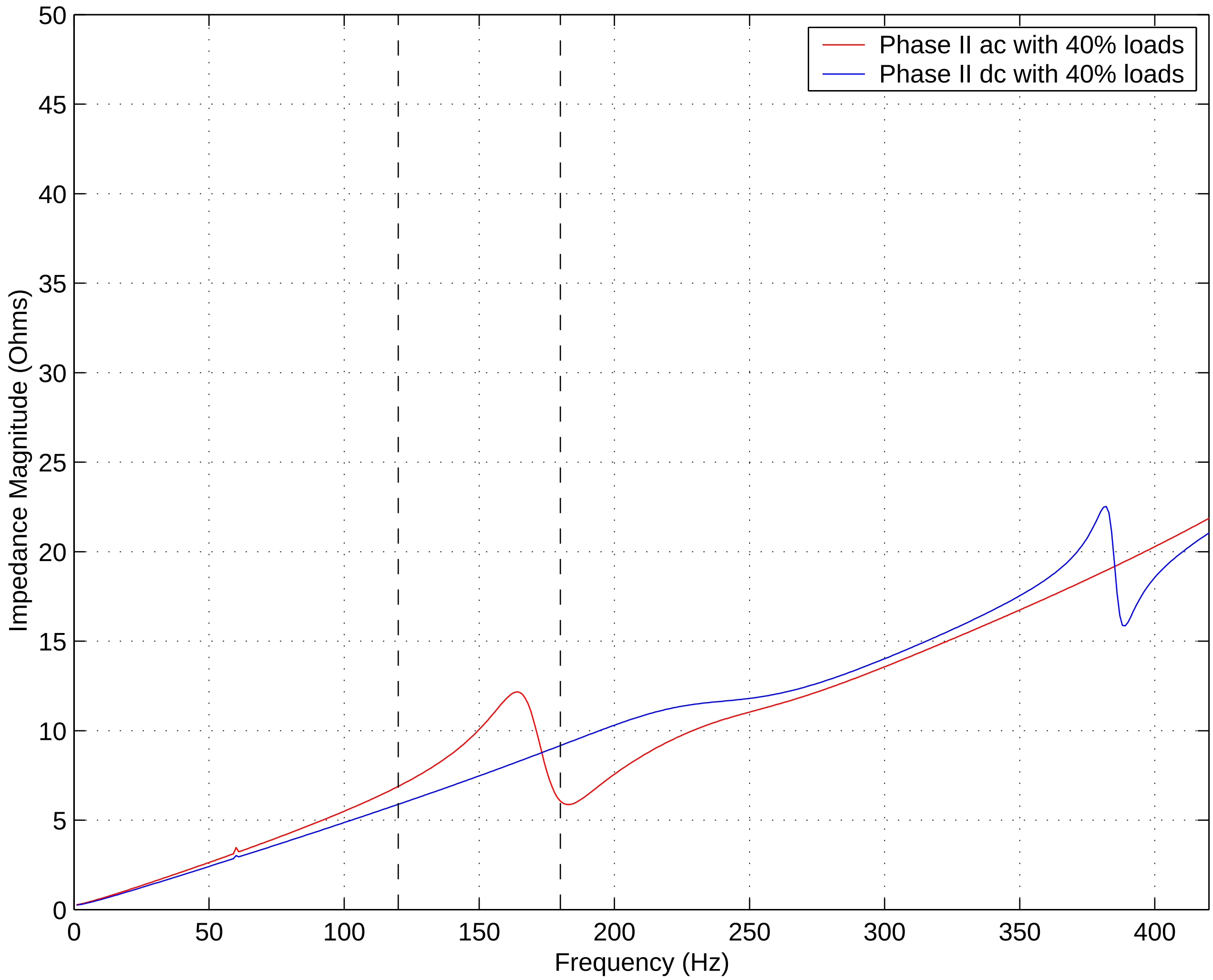
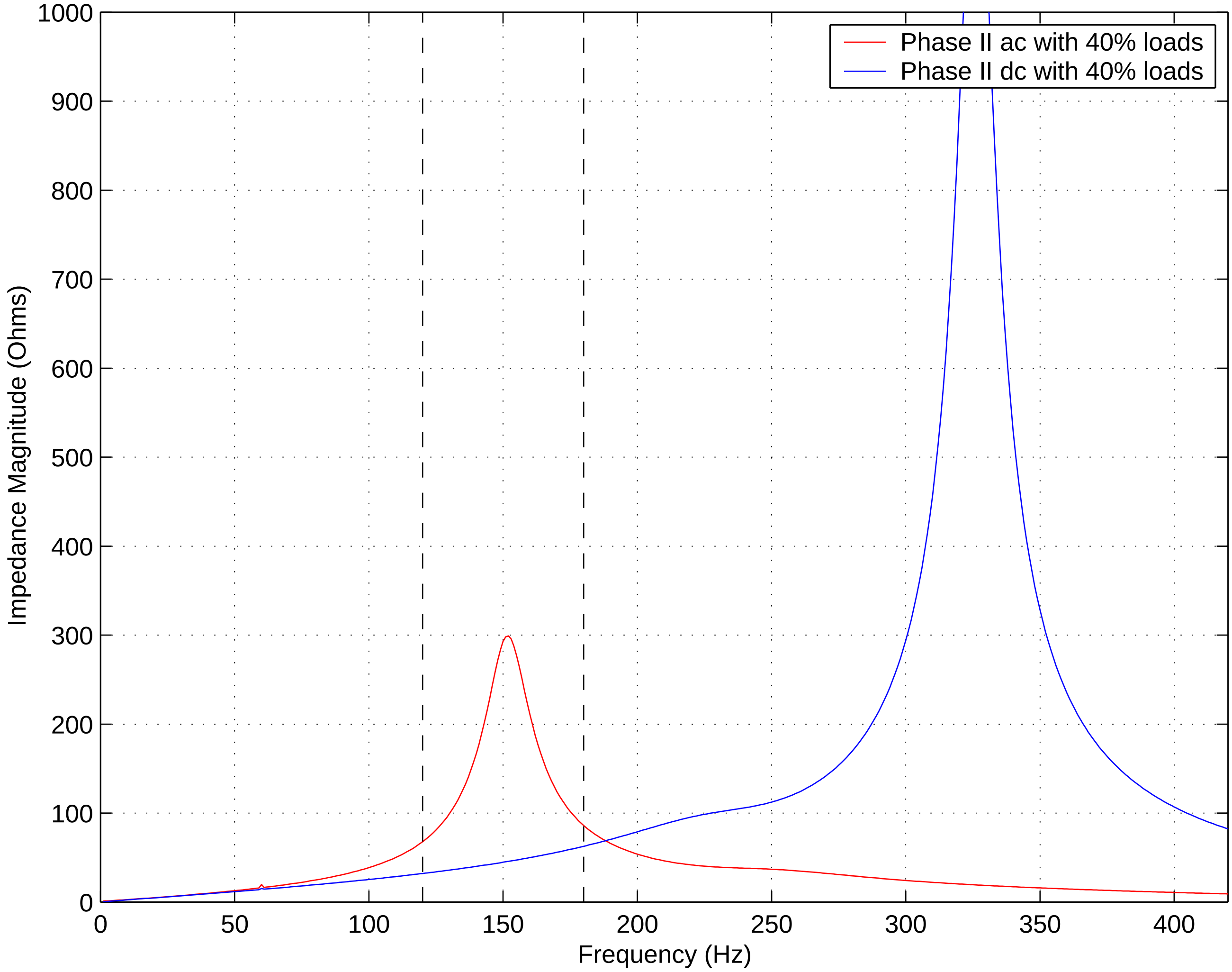


Figure D−166: Frequency Scan at Norwalk 345 kV − Cont 2



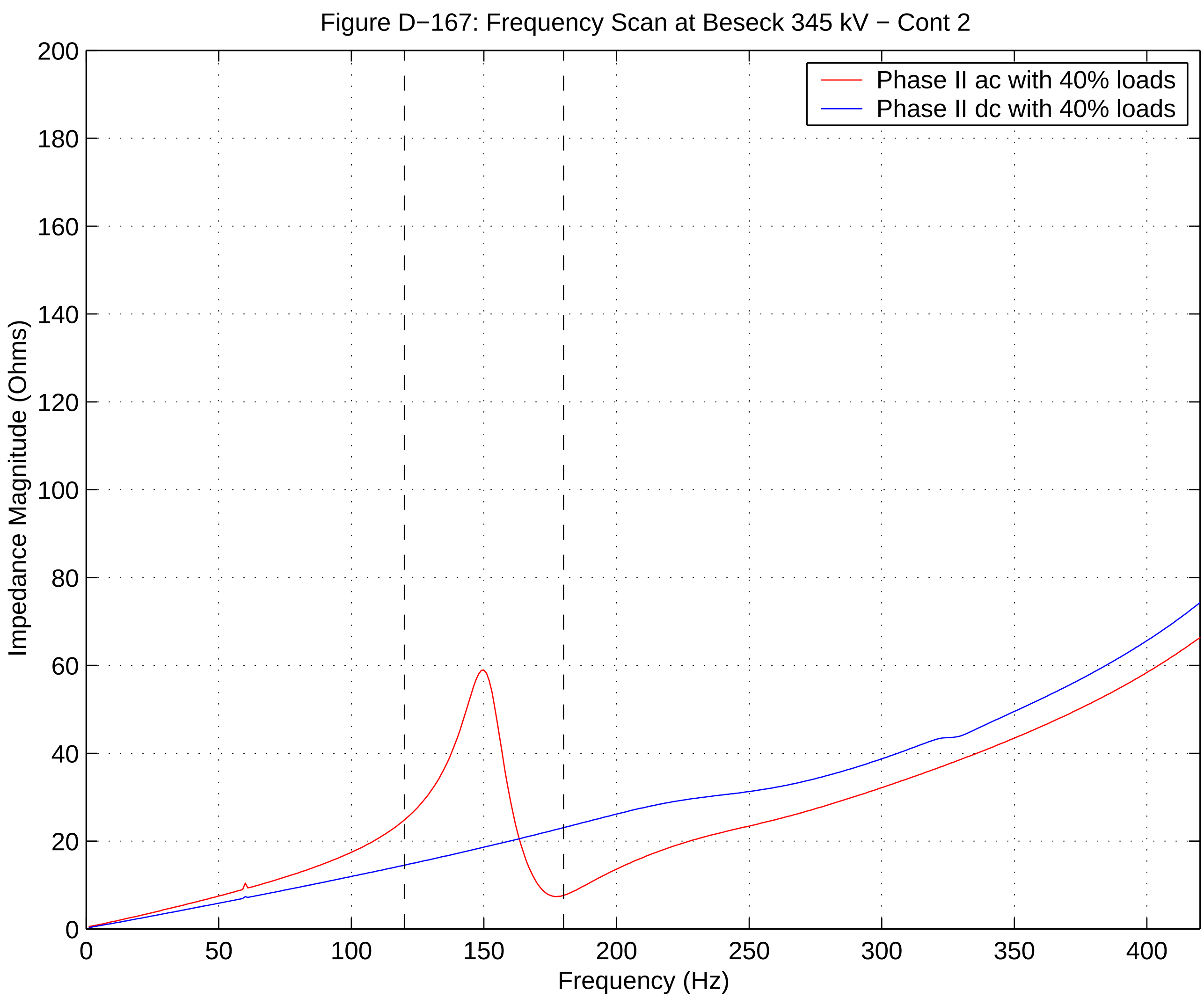
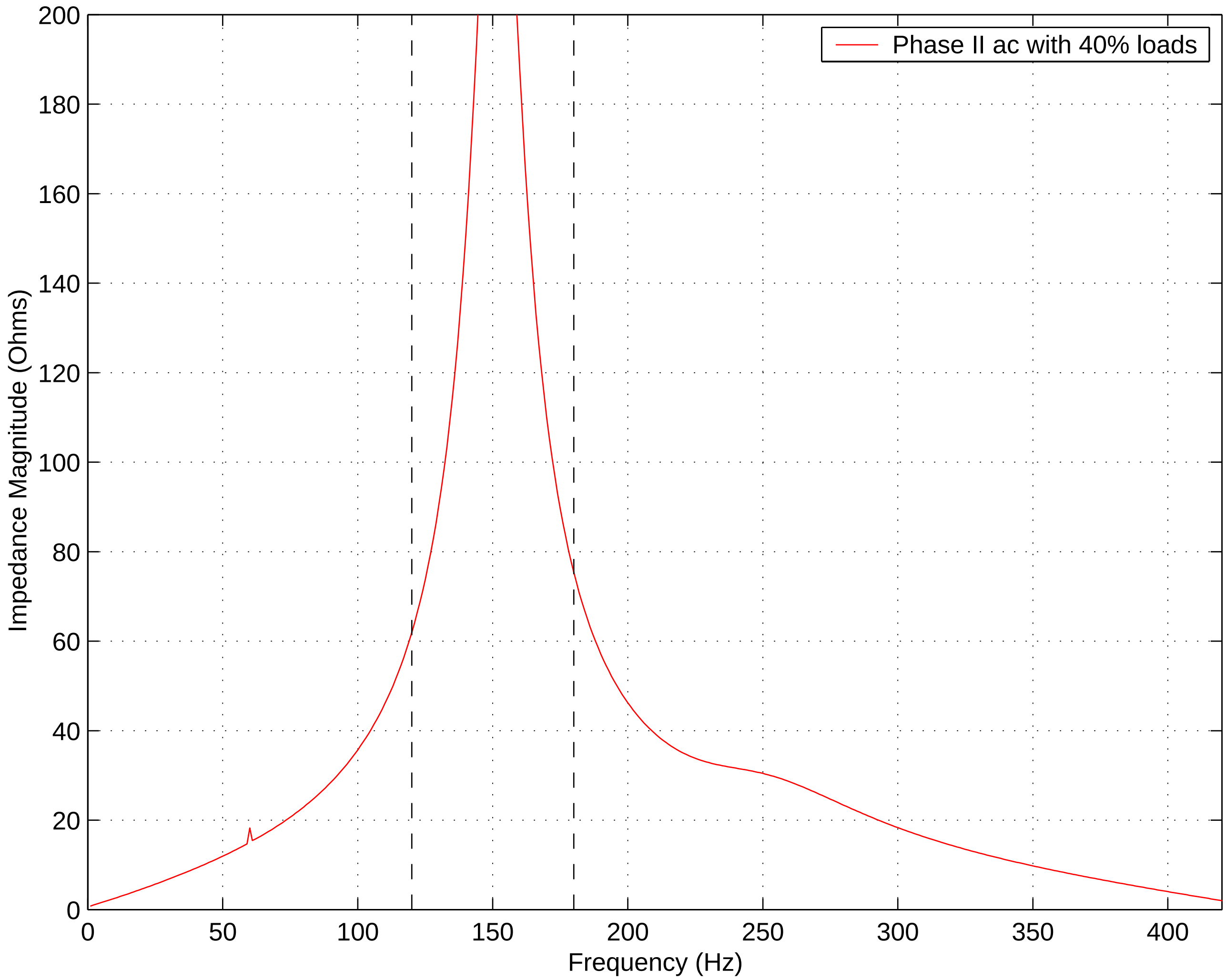


Figure D−167: Frequency Scan at Beseck 345 kV − Cont 2
Phase II ac with 40% loads
Phase II dc with 40% loads
Impedance Magnitude (Ohms)
Frequency (Hz)
0
20
40
60
80
100
120
140
160
180
200
0
50
100
150
200
250
300
350
400

Figure D−168: Frequency Scan at Devon 345 kV − Cont 2



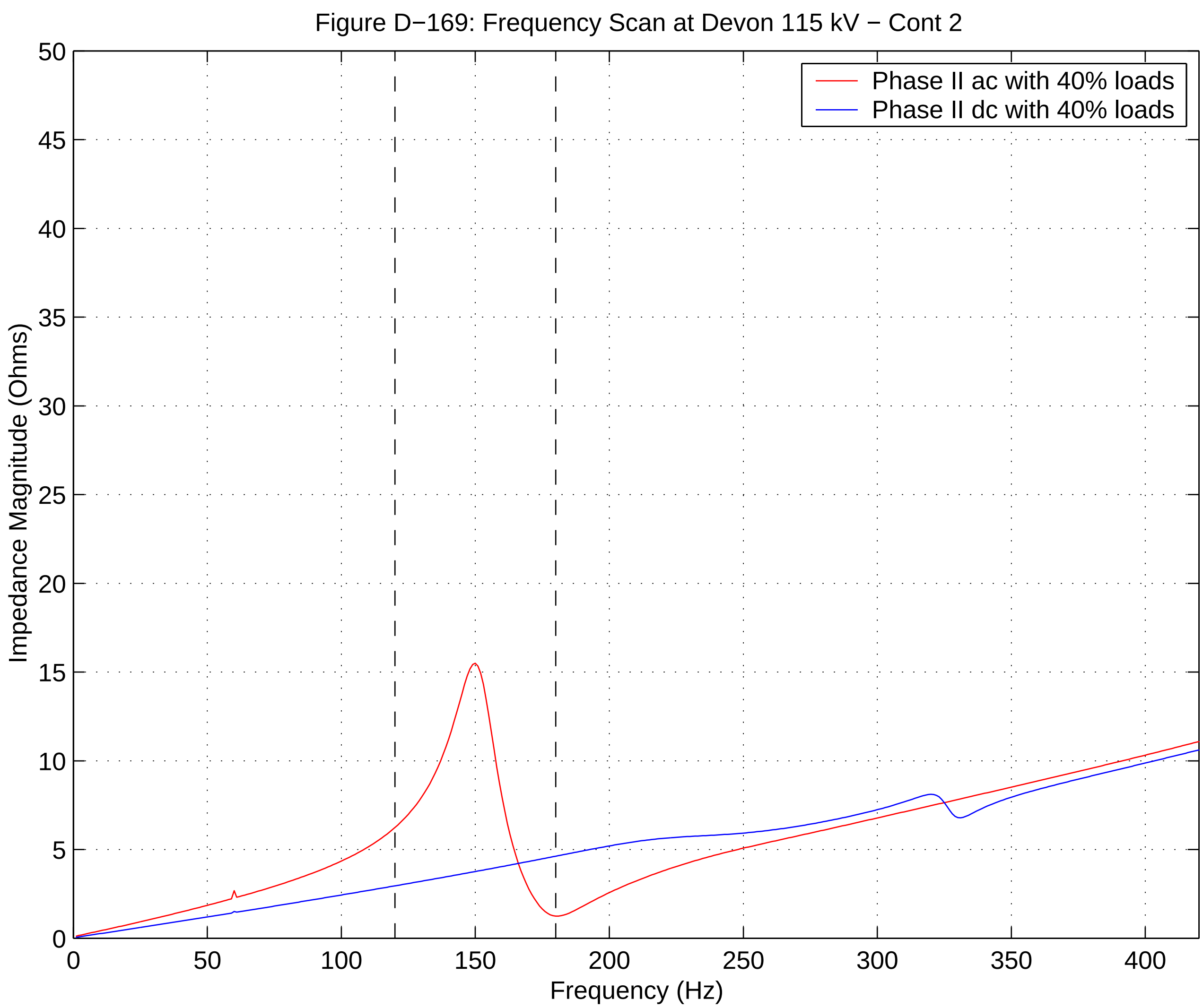


Figure D−169: Frequency Scan at Devon 115 kV − Cont 2
Phase II ac with 40% loads
Phase II dc with 40% loads
Impedance Magnitude (Ohms)
Frequency (Hz)
0
5
10
15
20
25
30
35
40
45
50
0
50
100
150
200
250
300
350
400

Figure D−170: Frequency Scan at Singer 345 kV − Cont 2

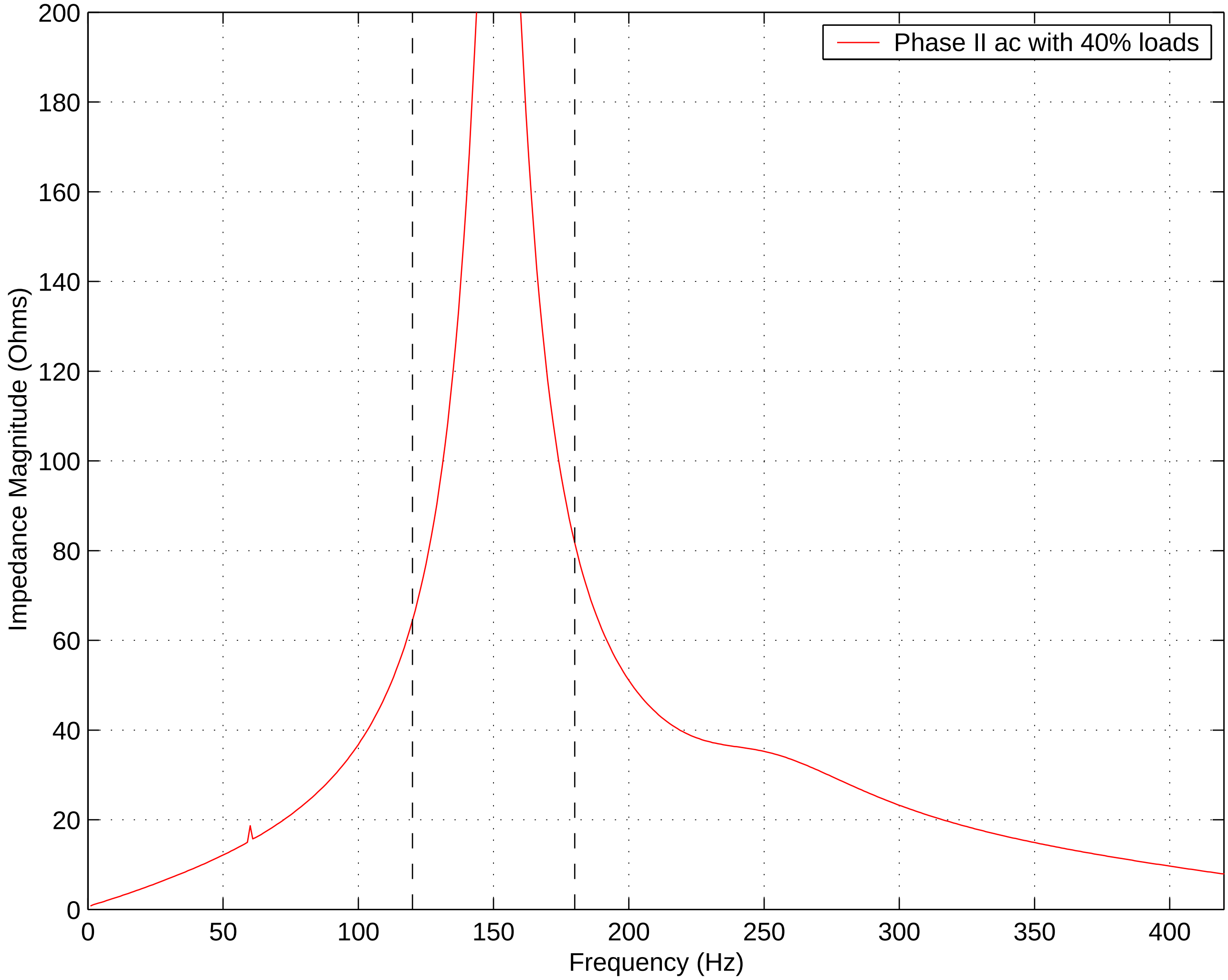
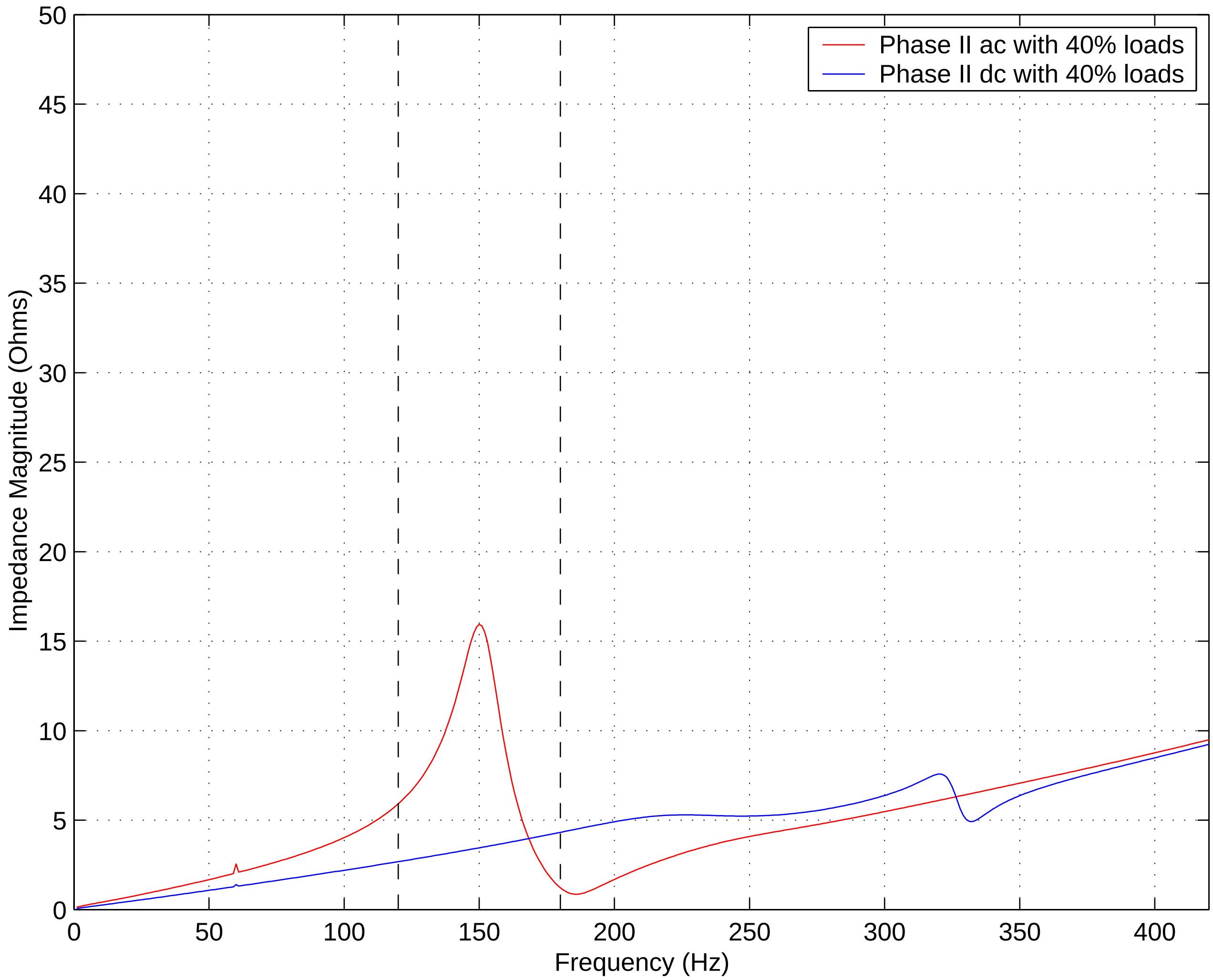


Figure D−171: Frequency Scan at Pequonnock 115 kV − Cont 2



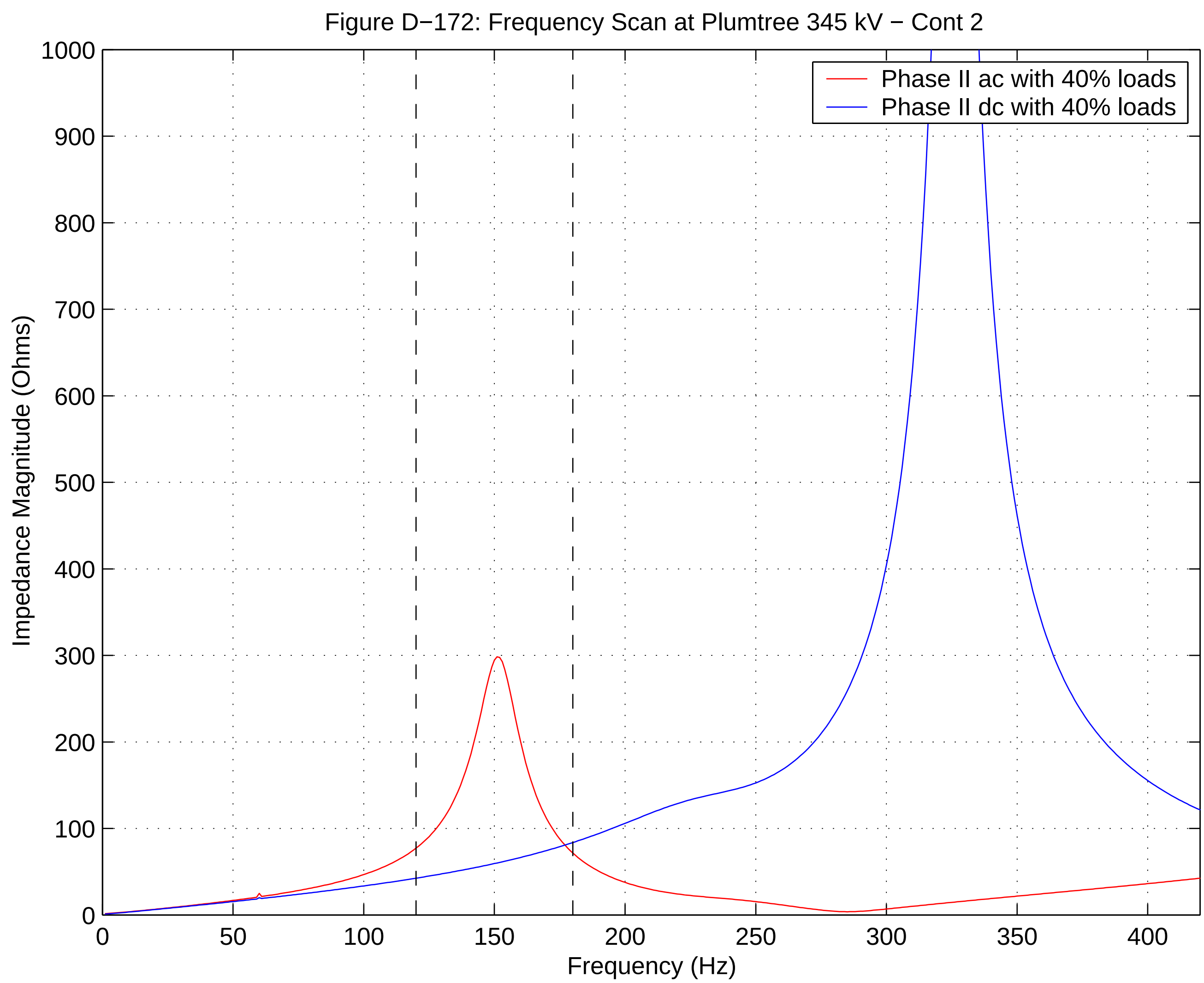


Figure D−172: Frequency Scan at Plumtree 345 kV − Cont 2
Phase II ac with 40% loads
Phase II dc with 40% loads
Impedance Magnitude (Ohms)
Frequency (Hz)
0
100
200
300
400
500
600
700
800
900
1000
0
50
100
150
200
250
300
350
400

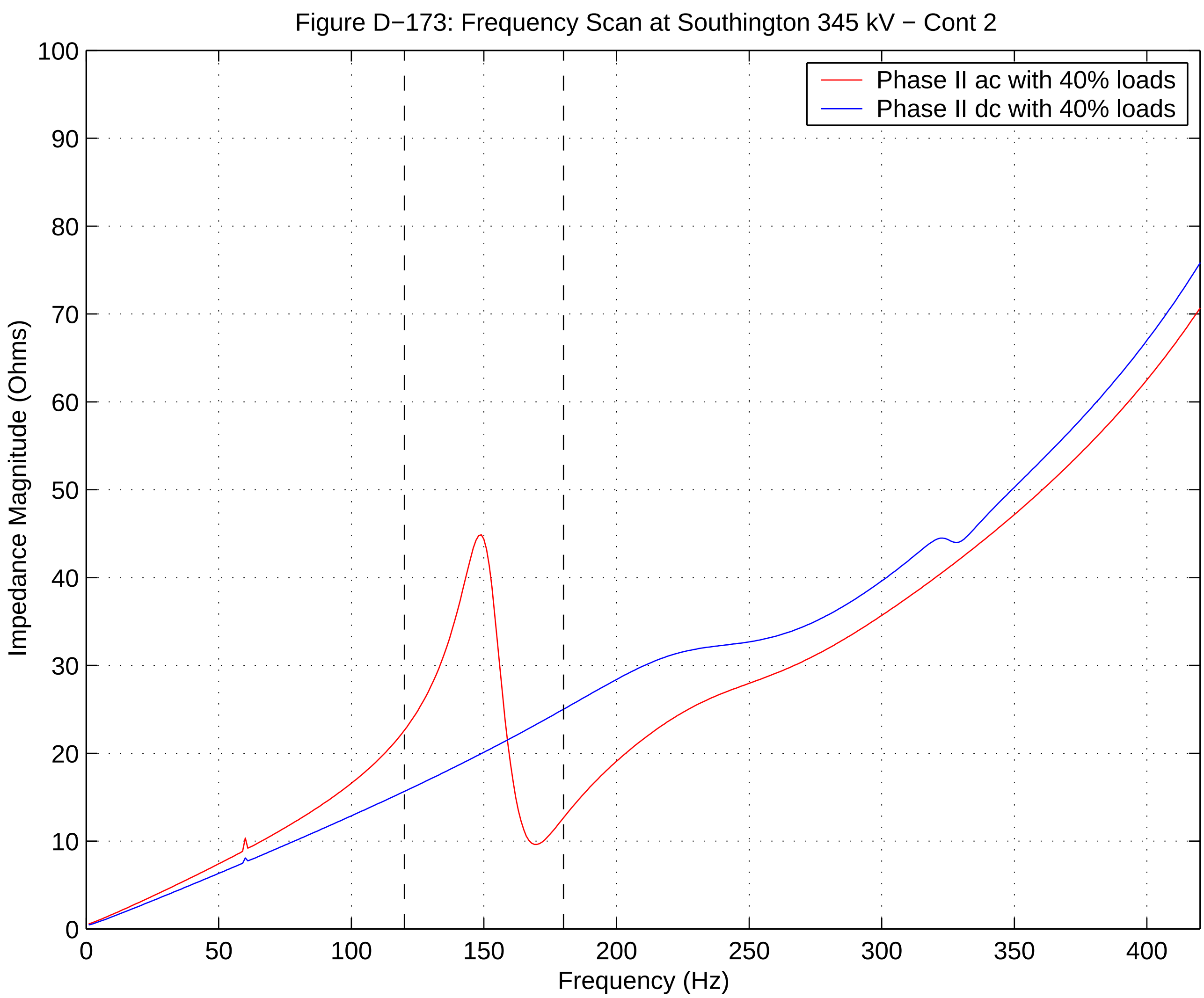


Figure D−173: Frequency Scan at Southington 345 kV − Cont 2
Phase II ac with 40% loads
Phase II dc with 40% loads
Impedance Magnitude (Ohms)
Frequency (Hz)
0
10
20
30
40
50
60
70
80
90
100
0
50
100
150
200
250
300
350
400

Figure D−174: Frequency Scan at Woodmont 115 kV − Cont 2

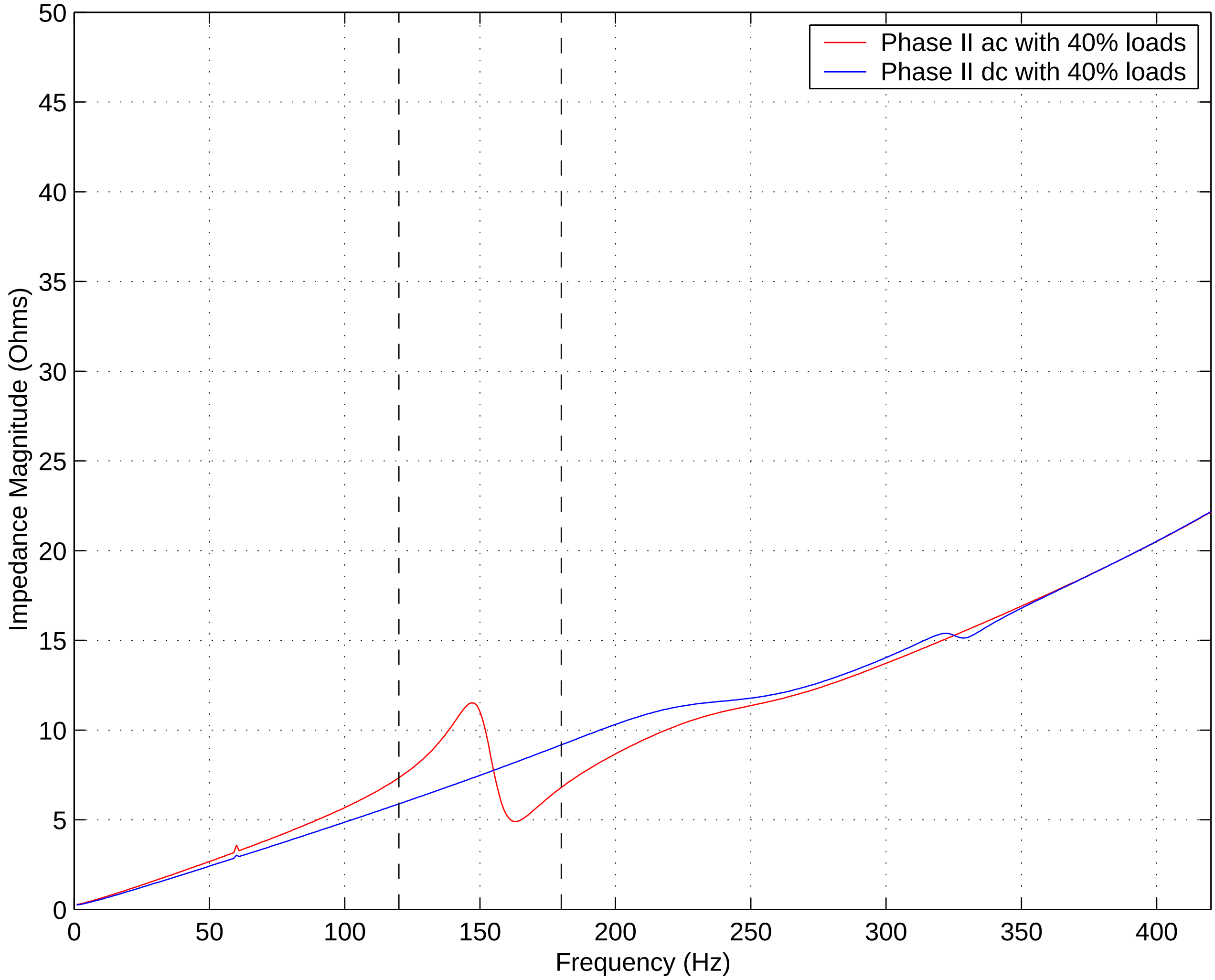
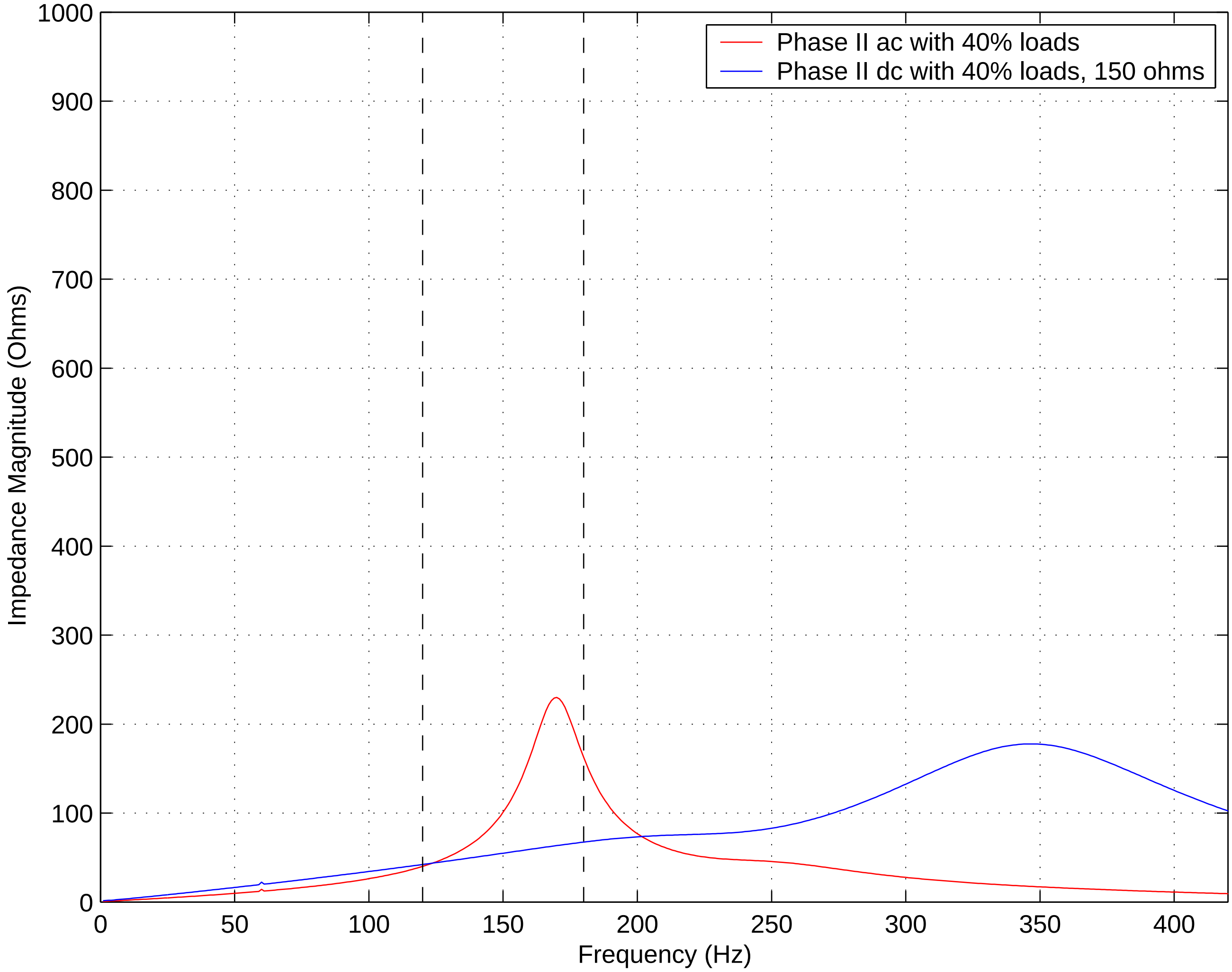


Figure D−175: Frequency Scan at Norwalk 345 kV



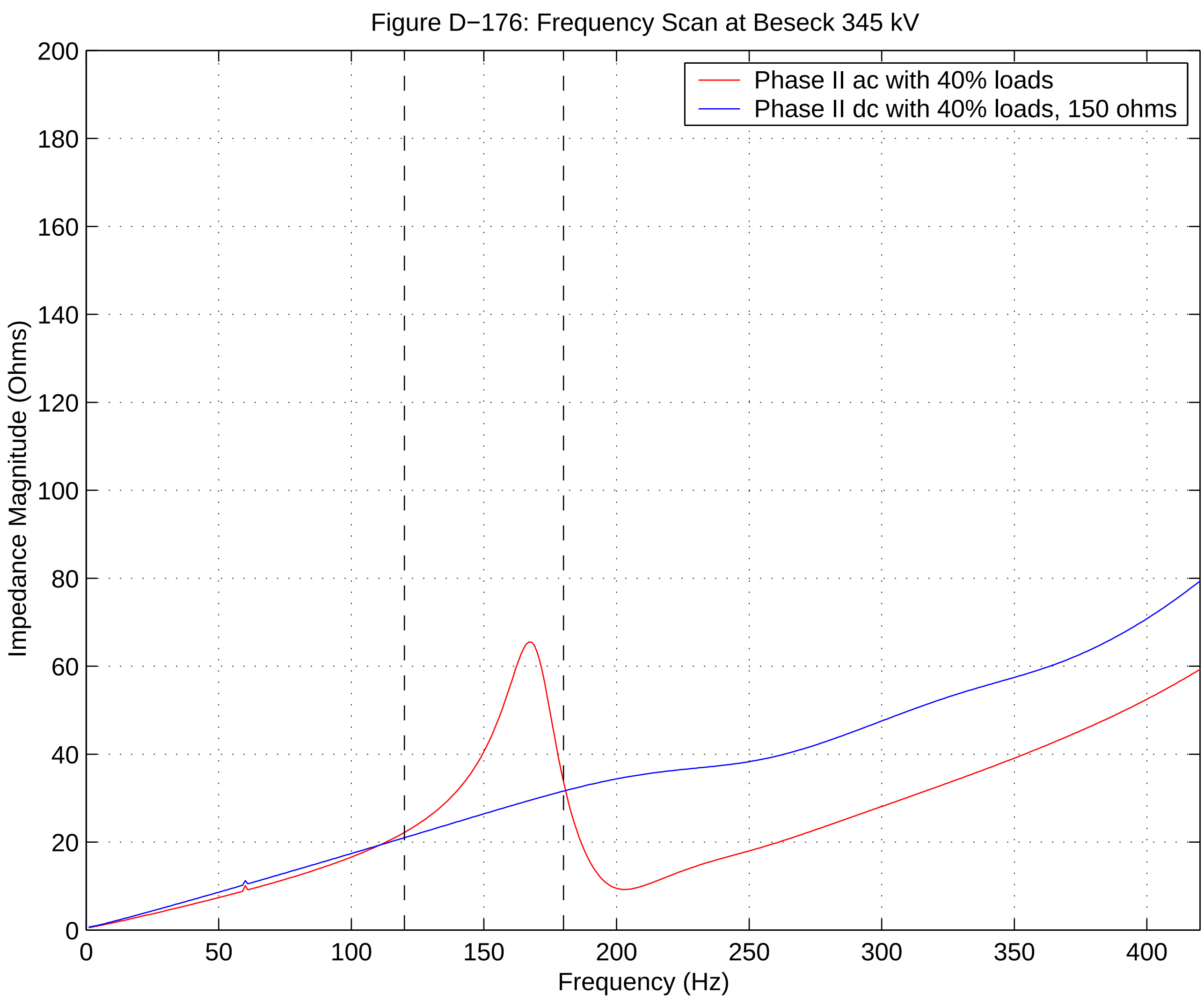


Figure D−176: Frequency Scan at Beseck 345 kV
Phase II ac with 40% loads
Phase II dc with 40% loads, 150 ohms
Impedance Magnitude (Ohms)
Frequency (Hz)
0
20
40
60
80
100
120
140
160
180
200
0
50
100
150
200
250
300
350
400

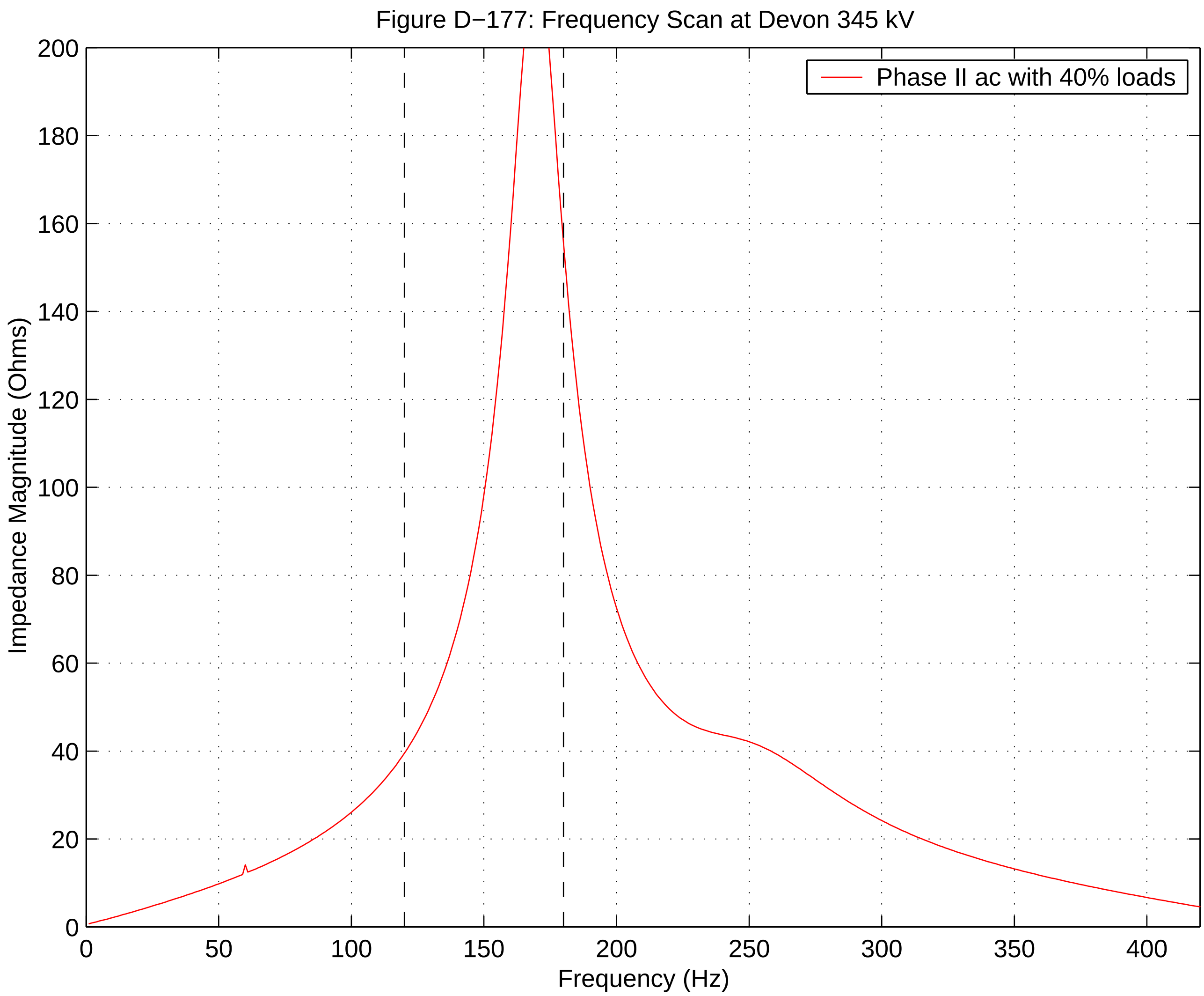


Figure D−177: Frequency Scan at Devon 345 kV
Phase II ac with 40% loads
Impedance Magnitude (Ohms)
Frequency (Hz)
0
20
40
60
80
100
120
140
160
180
200
0
50
100
150
200
250
300
350
400

Figure D−178: Frequency Scan at Devon 115 kV

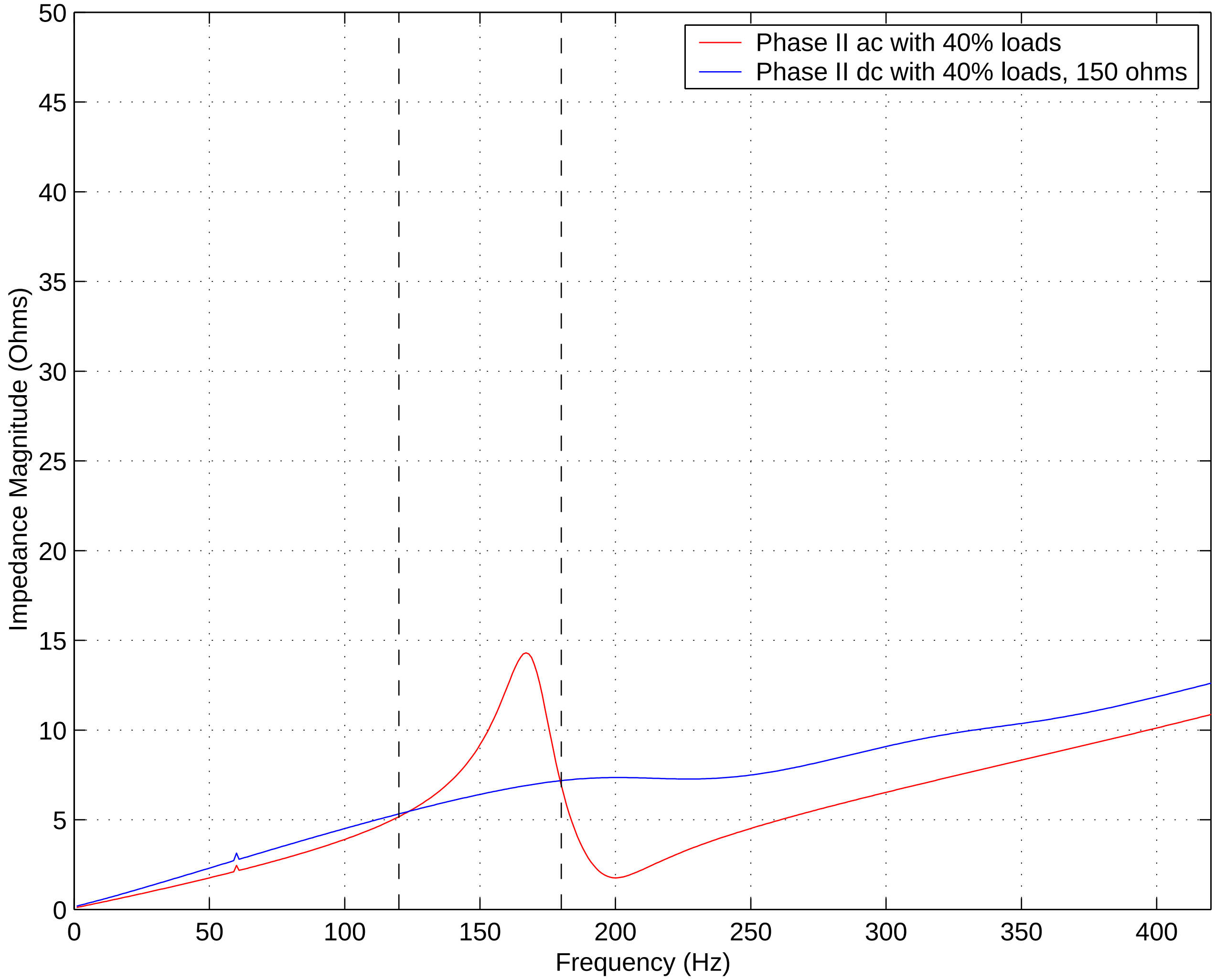


Figure D−179: Frequency Scan at Singer 345 kV

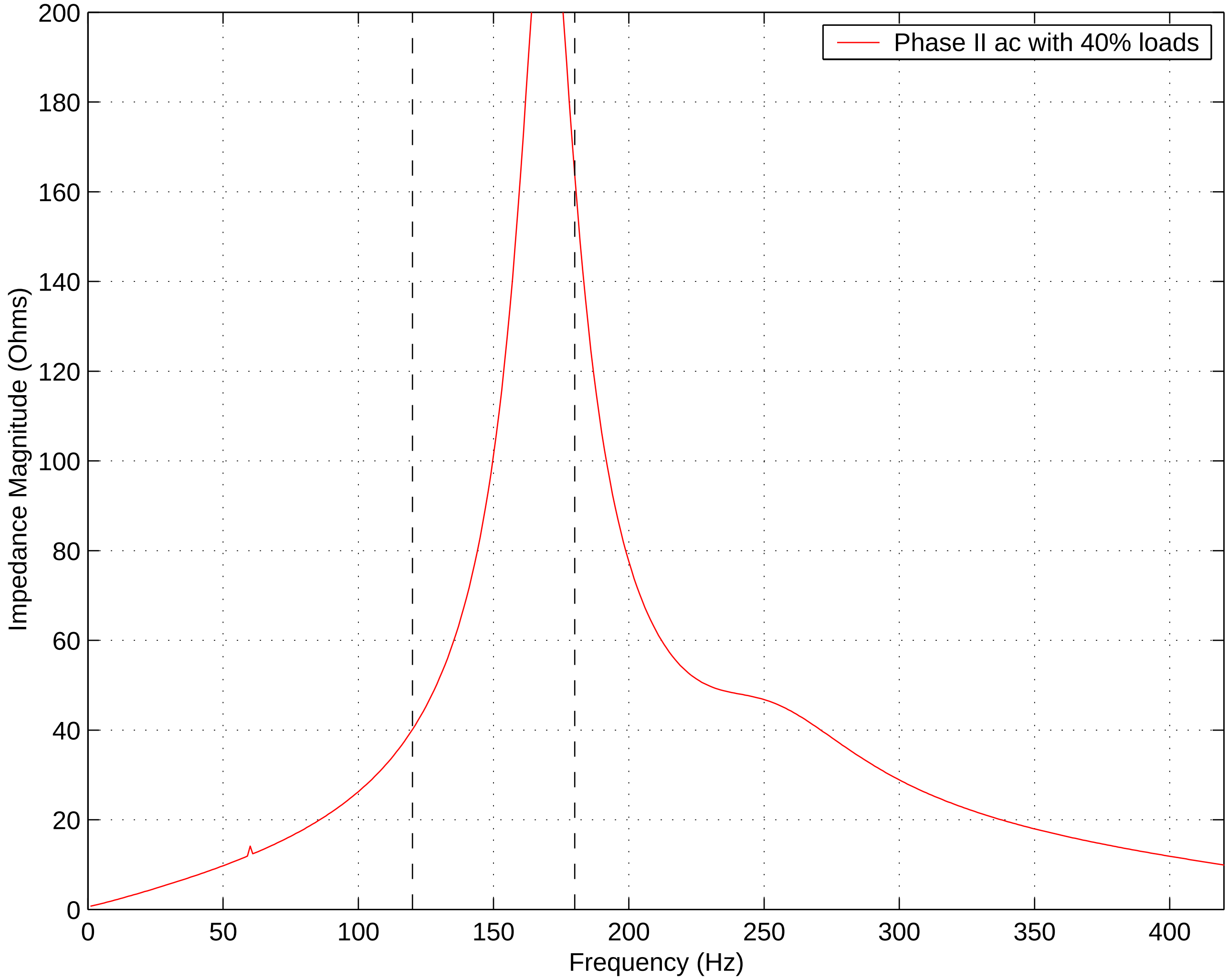
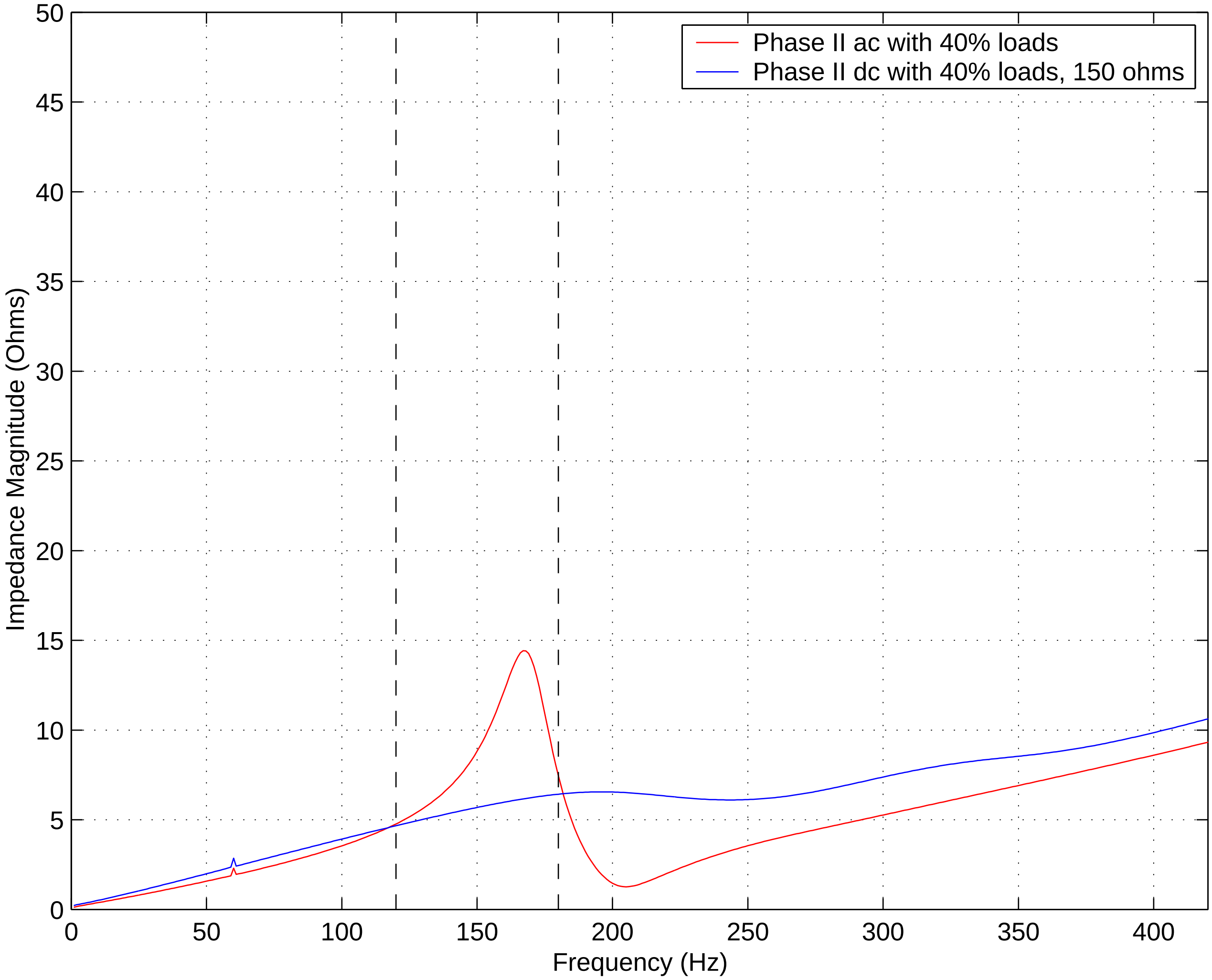


Figure D−180: Frequency Scan at Pequonnock 115 kV



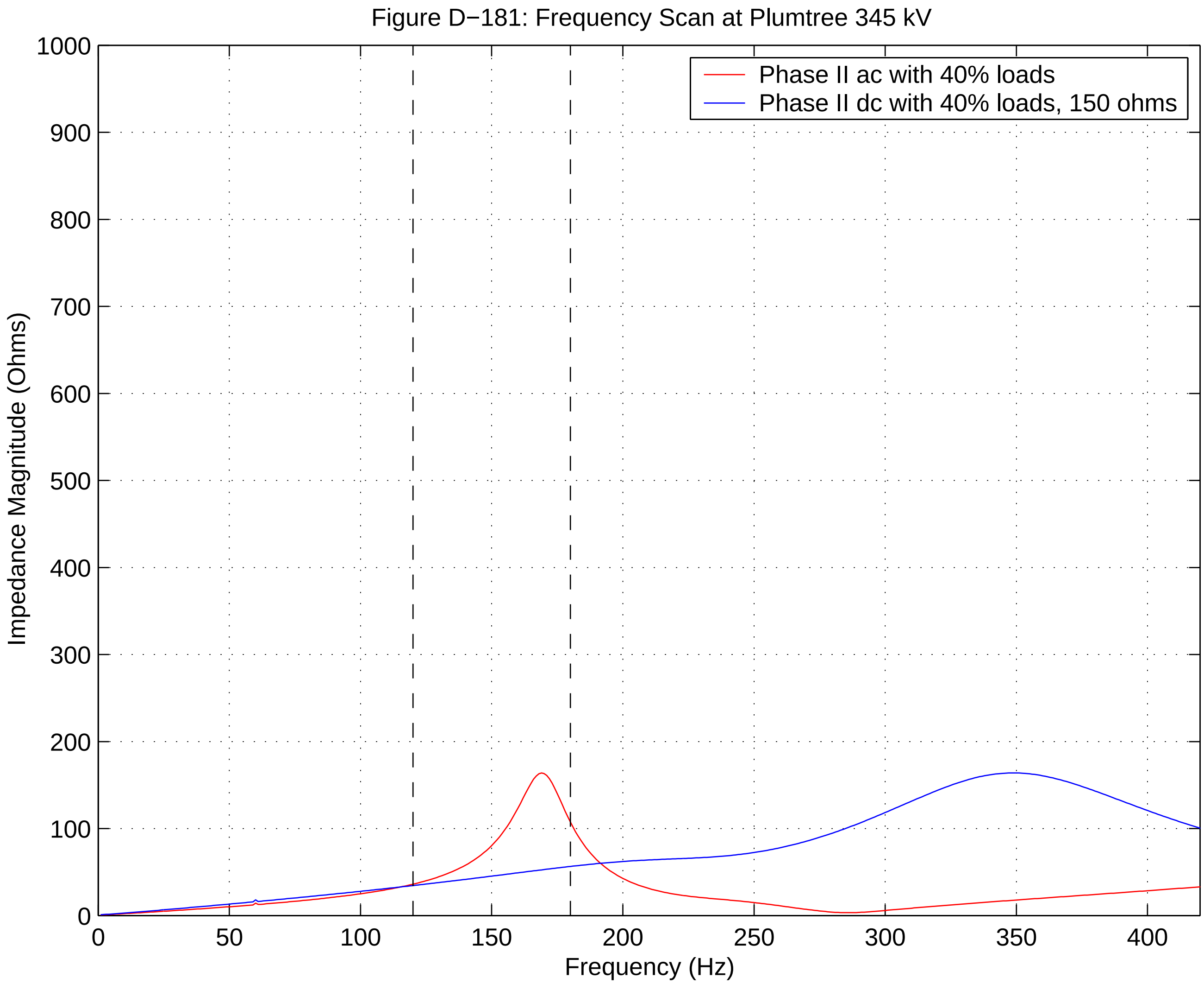


Figure D−181: Frequency Scan at Plumtree 345 kV
Phase II ac with 40% loads
Phase II dc with 40% loads, 150 ohms
Impedance Magnitude (Ohms)
Frequency (Hz)
0
100
200
300
400
500
600
700
800
900
1000
0
50
100
150
200
250
300
350
400

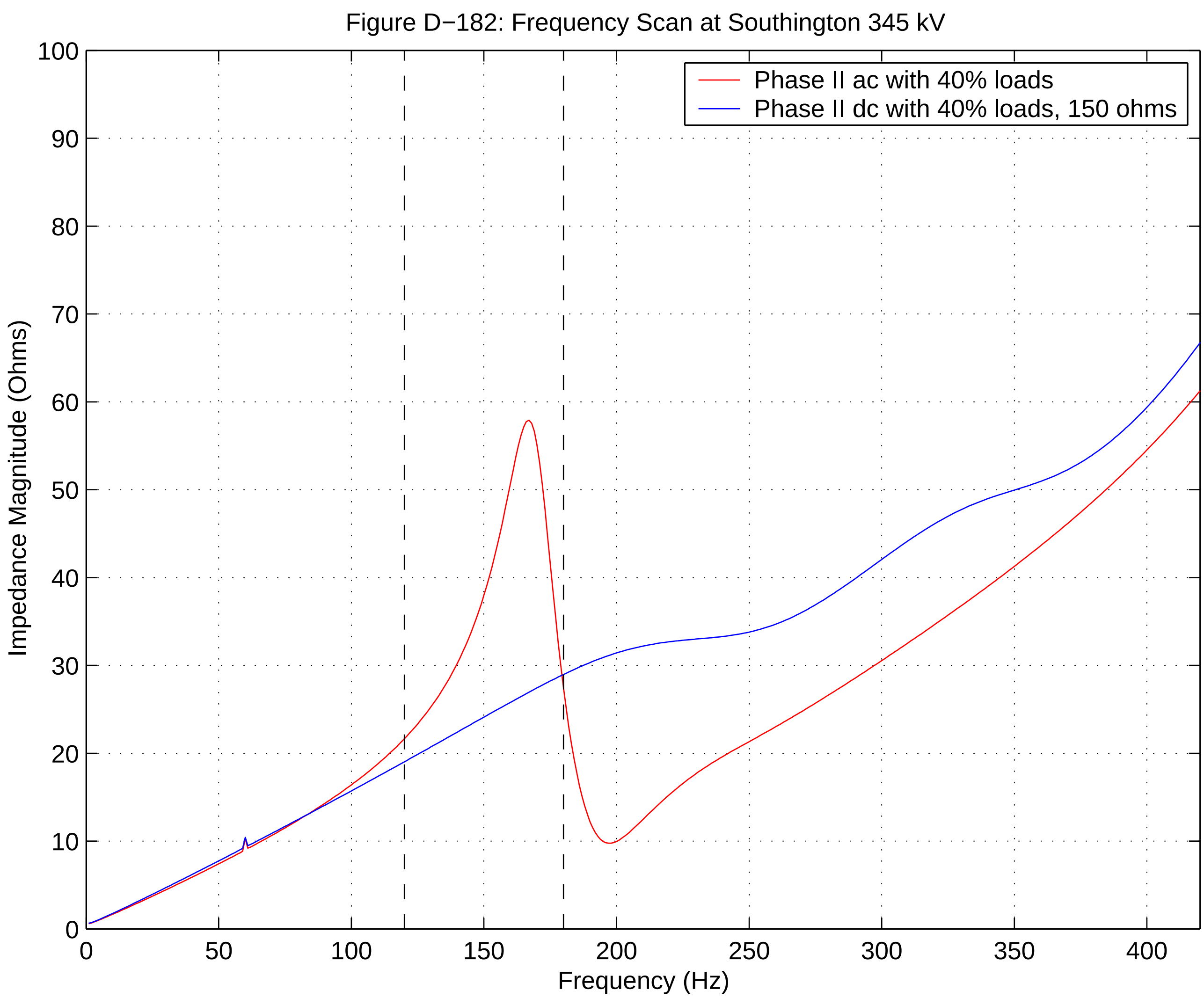


Figure D−182: Frequency Scan at Southington 345 kV
Phase II ac with 40% loads
Phase II dc with 40% loads, 150 ohms
Impedance Magnitude (Ohms)
Frequency (Hz)
0
10
20
30
40
50
60
70
80
90
100
0
50
100
150
200
250
300
350
400

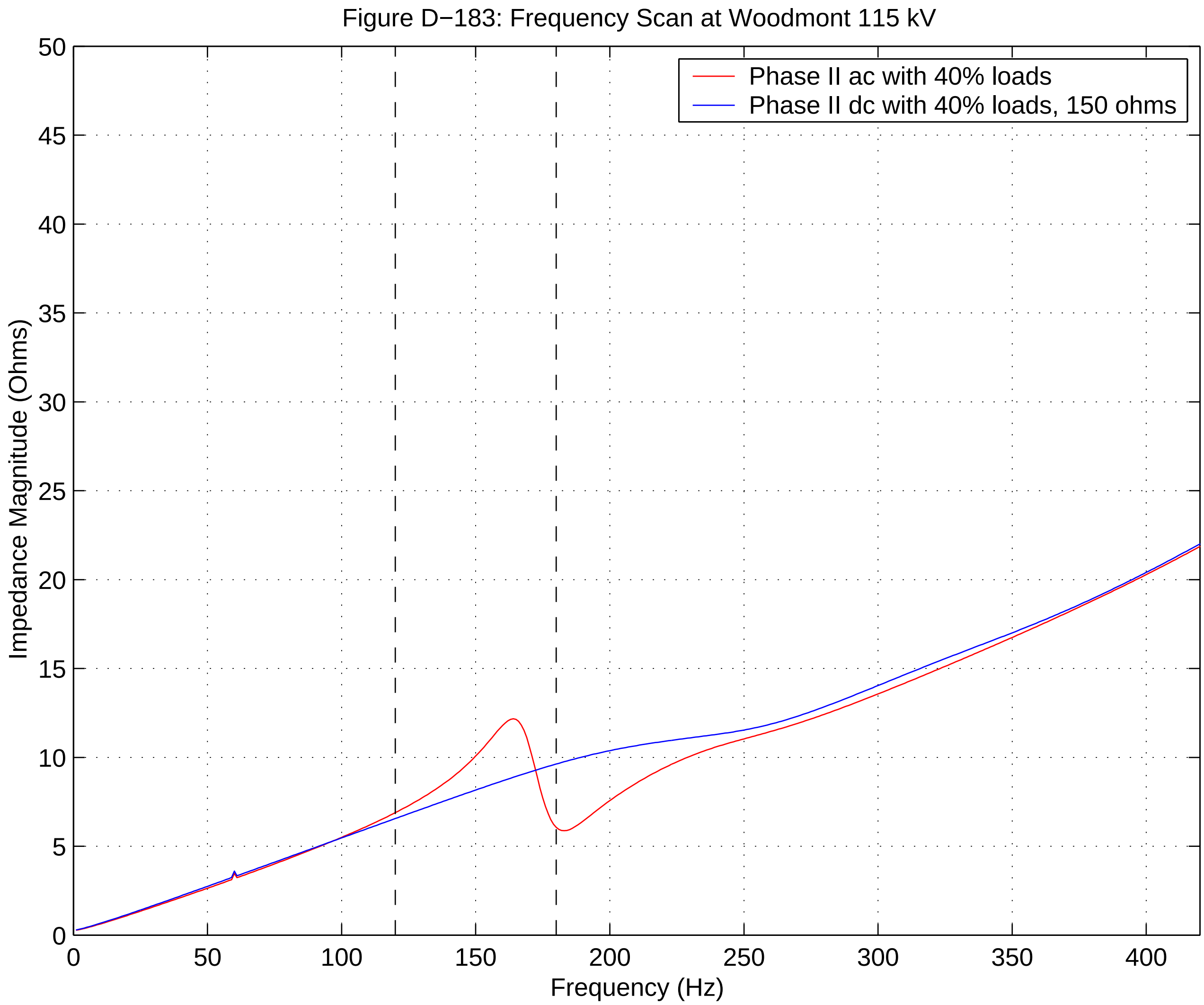


Figure D−183: Frequency Scan at Woodmont 115 kV
Phase II ac with 40% loads
Phase II dc with 40% loads, 150 ohms
Impedance Magnitude (Ohms)
Frequency (Hz)
0
5
10
15
20
25
30
35
40
45
50
0
50
100
150
200
250
300
350
400

Figure D−184: Frequency Scan at Norwalk 345 kV − Cont 2

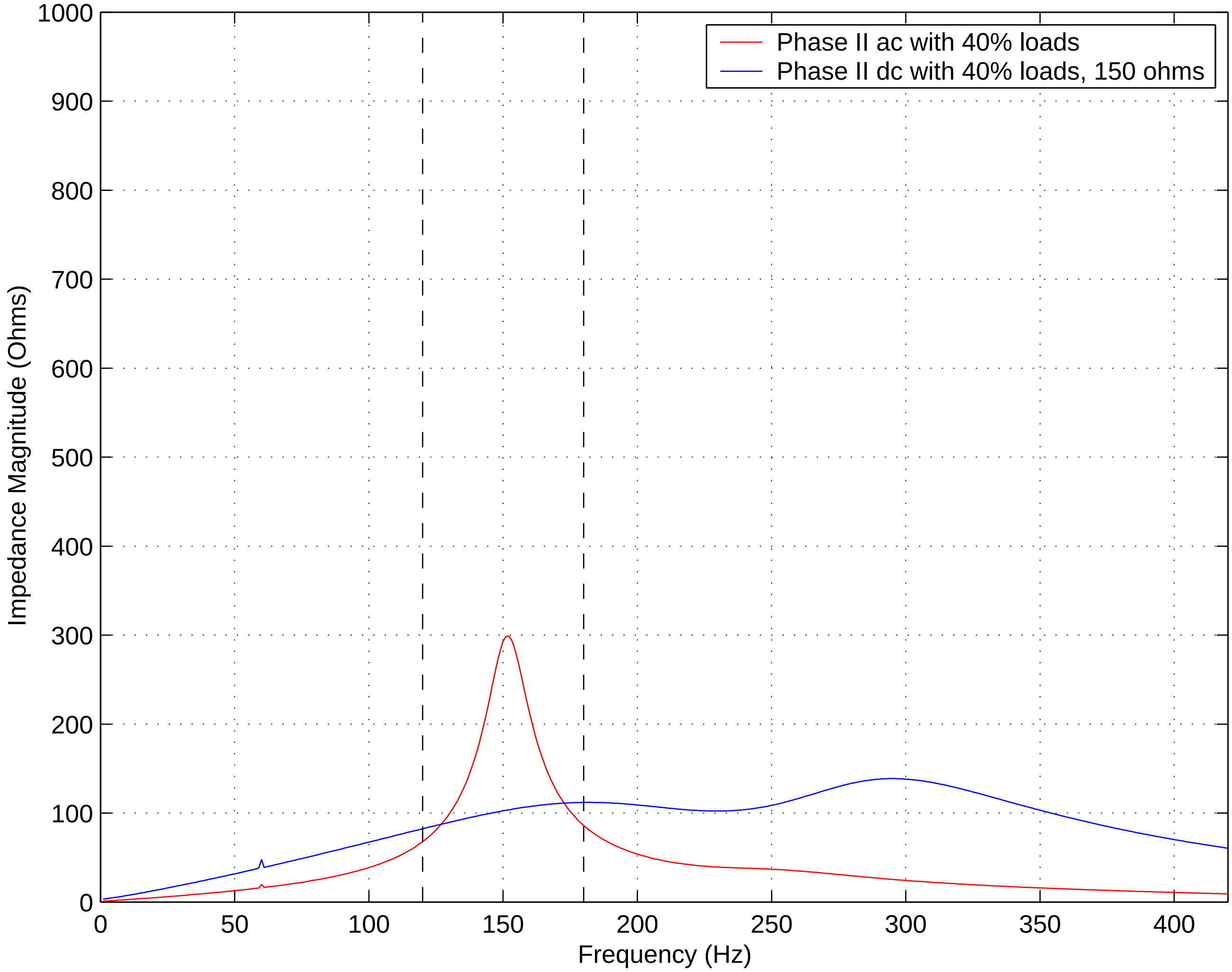


Figure D−185: Frequency Scan at Beseck 345 kV − Cont 2

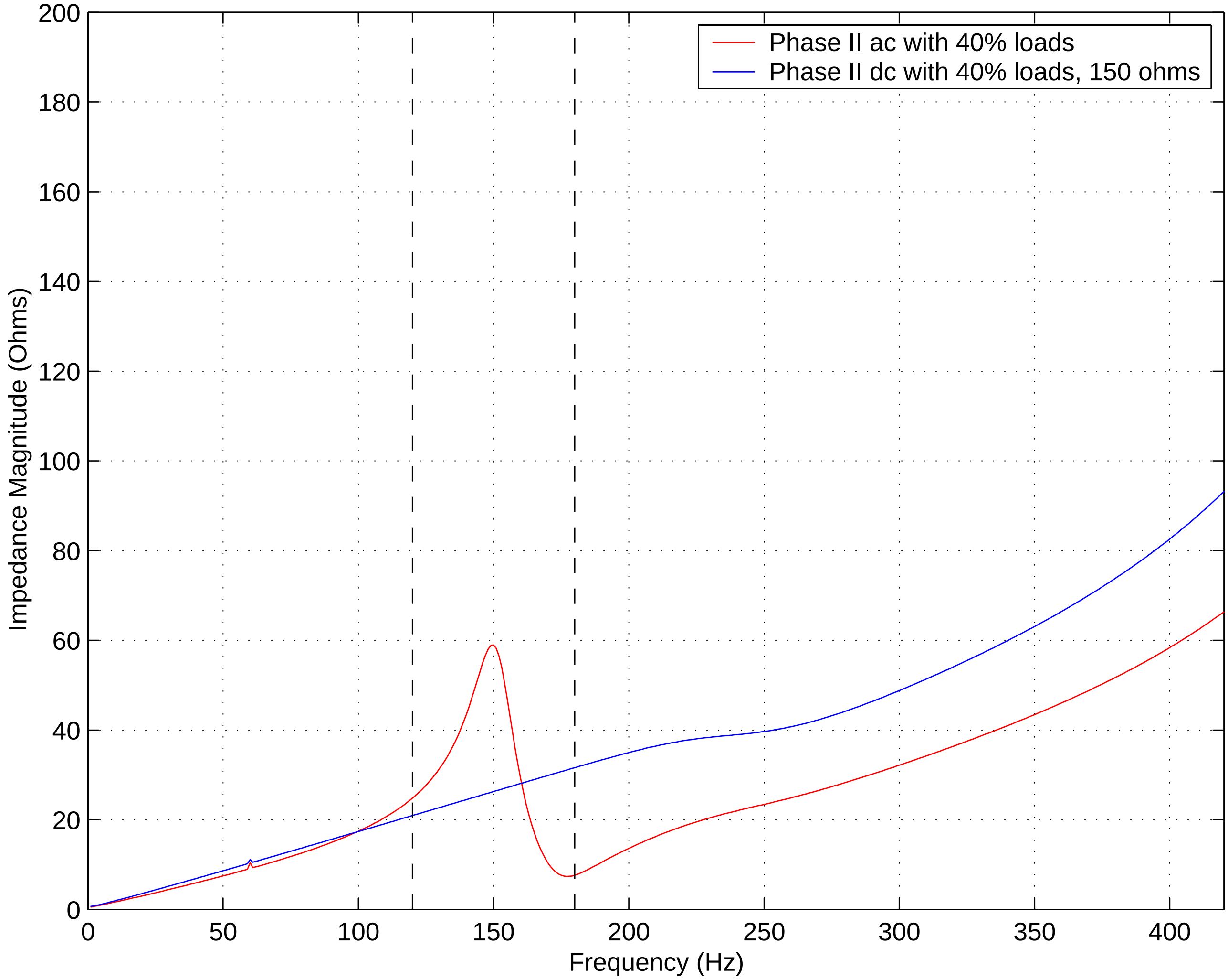


Figure D−186: Frequency Scan at Devon 345 kV − Cont 2

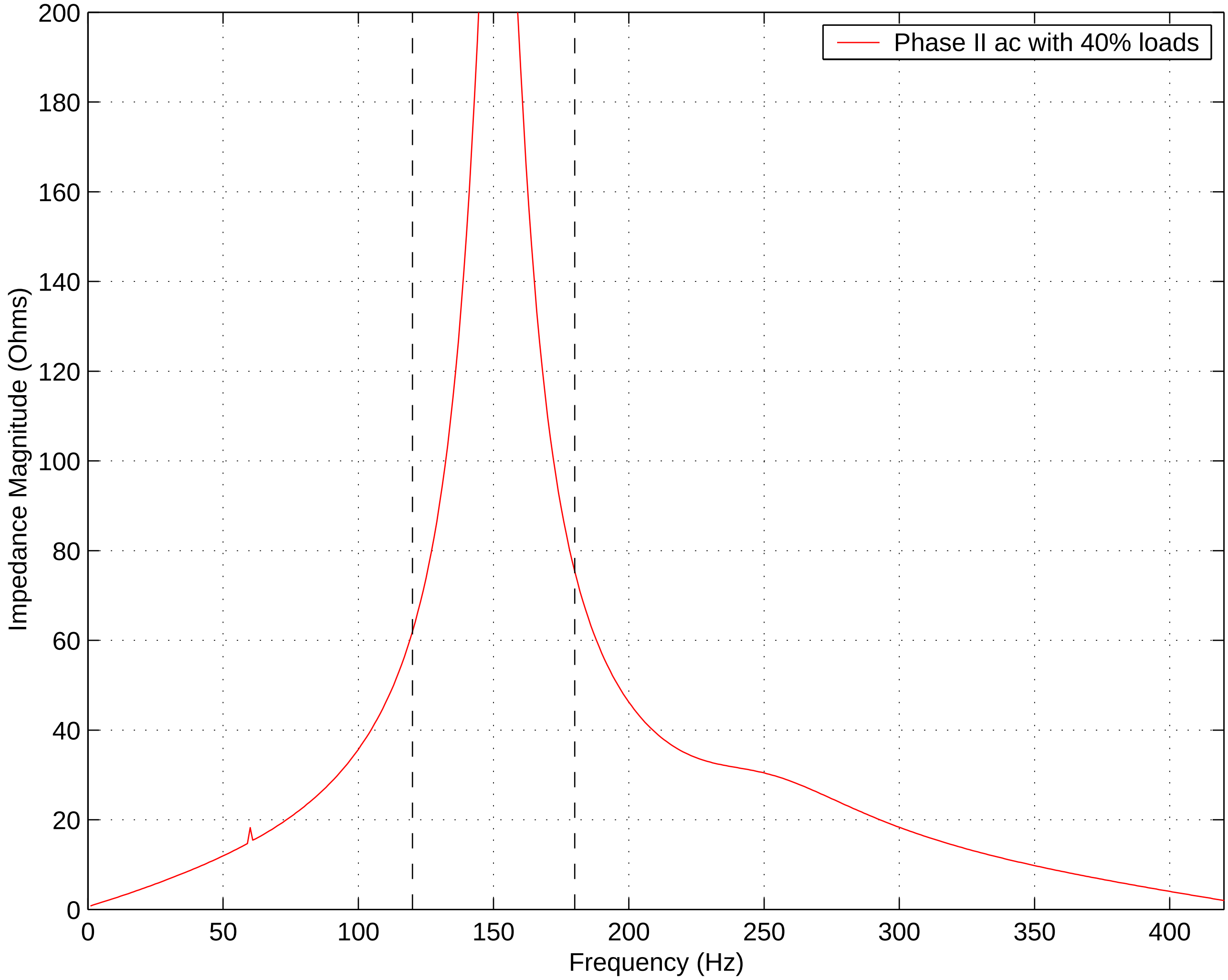
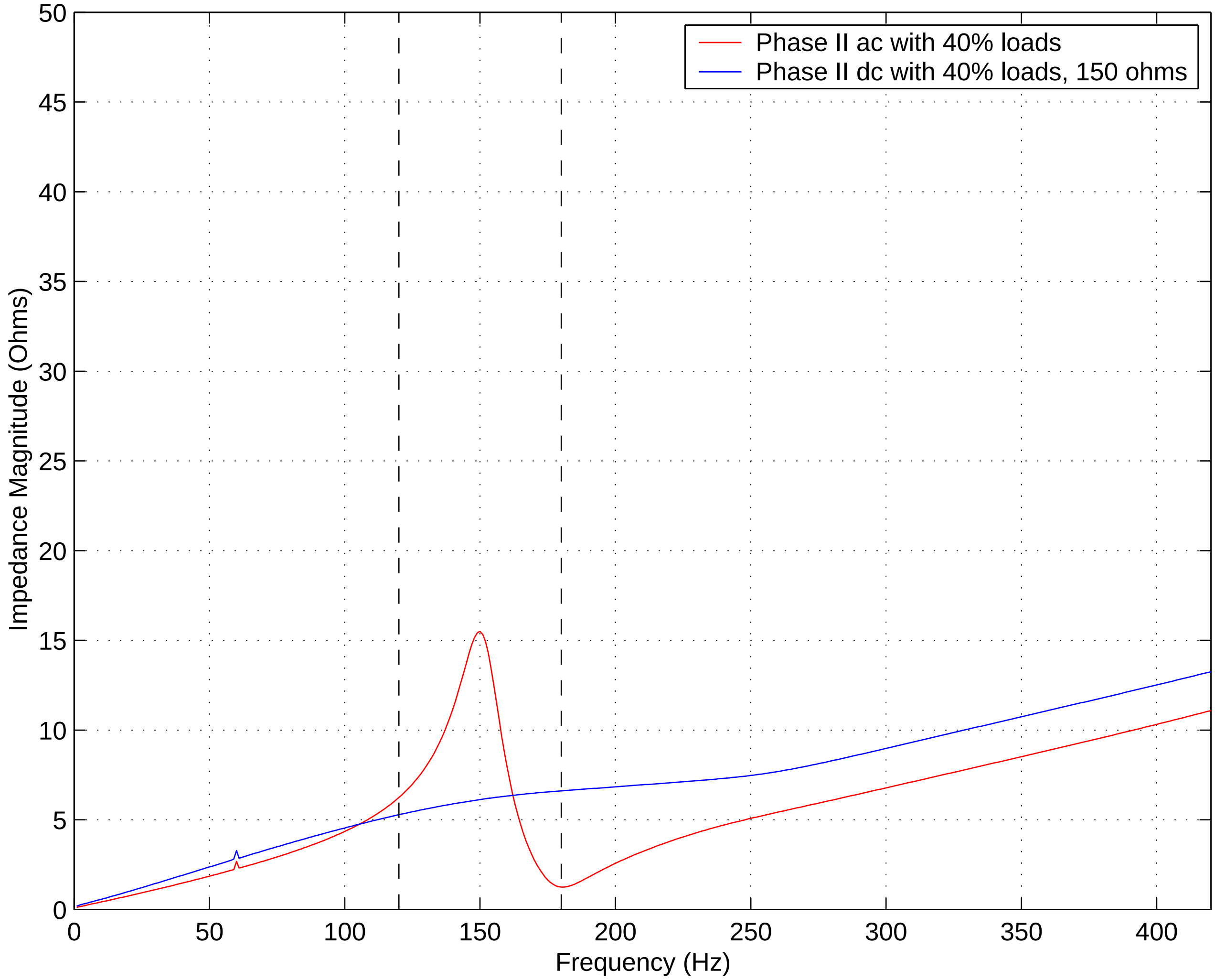


Figure D−187: Frequency Scan at Devon 115 kV − Cont 2



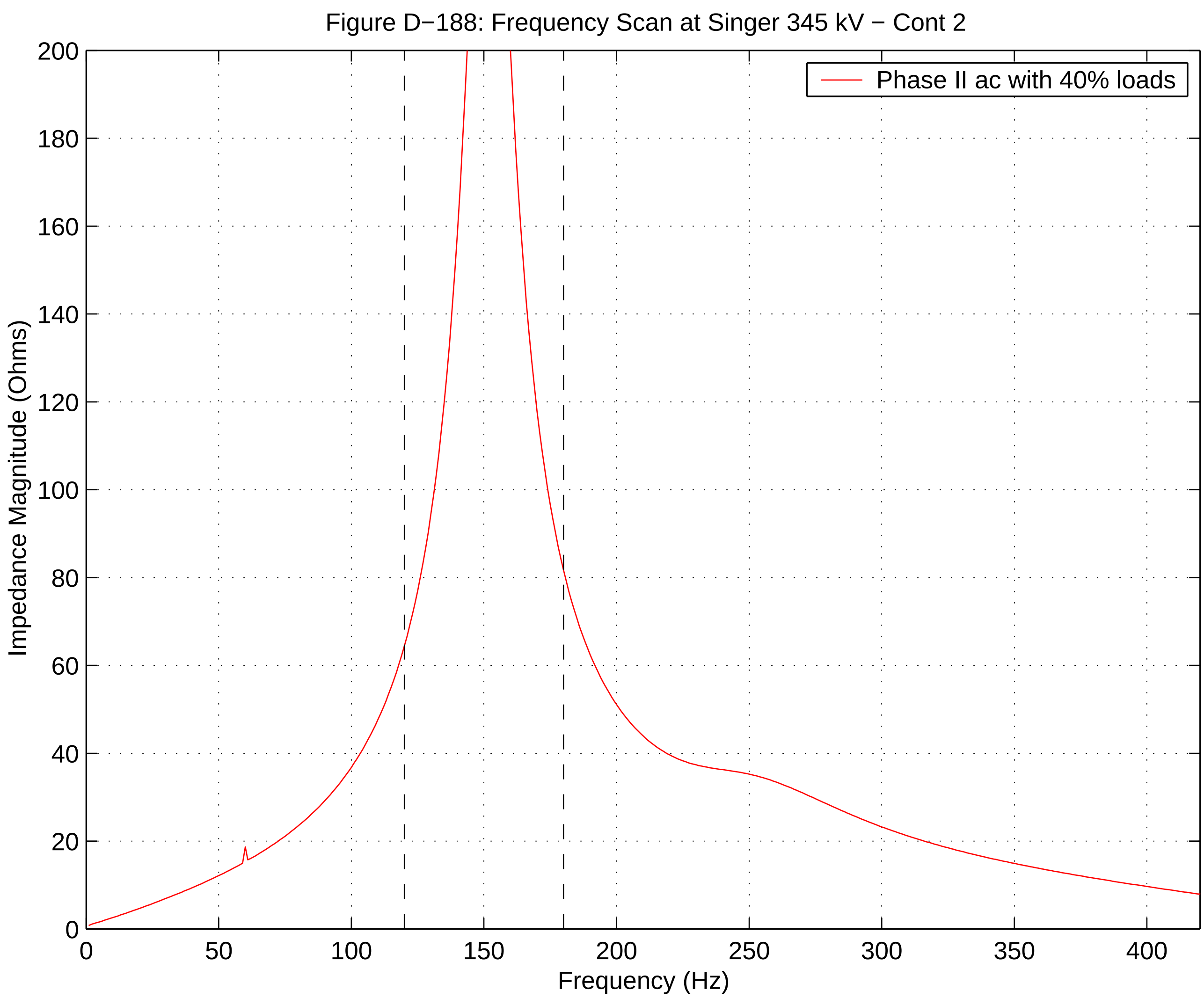
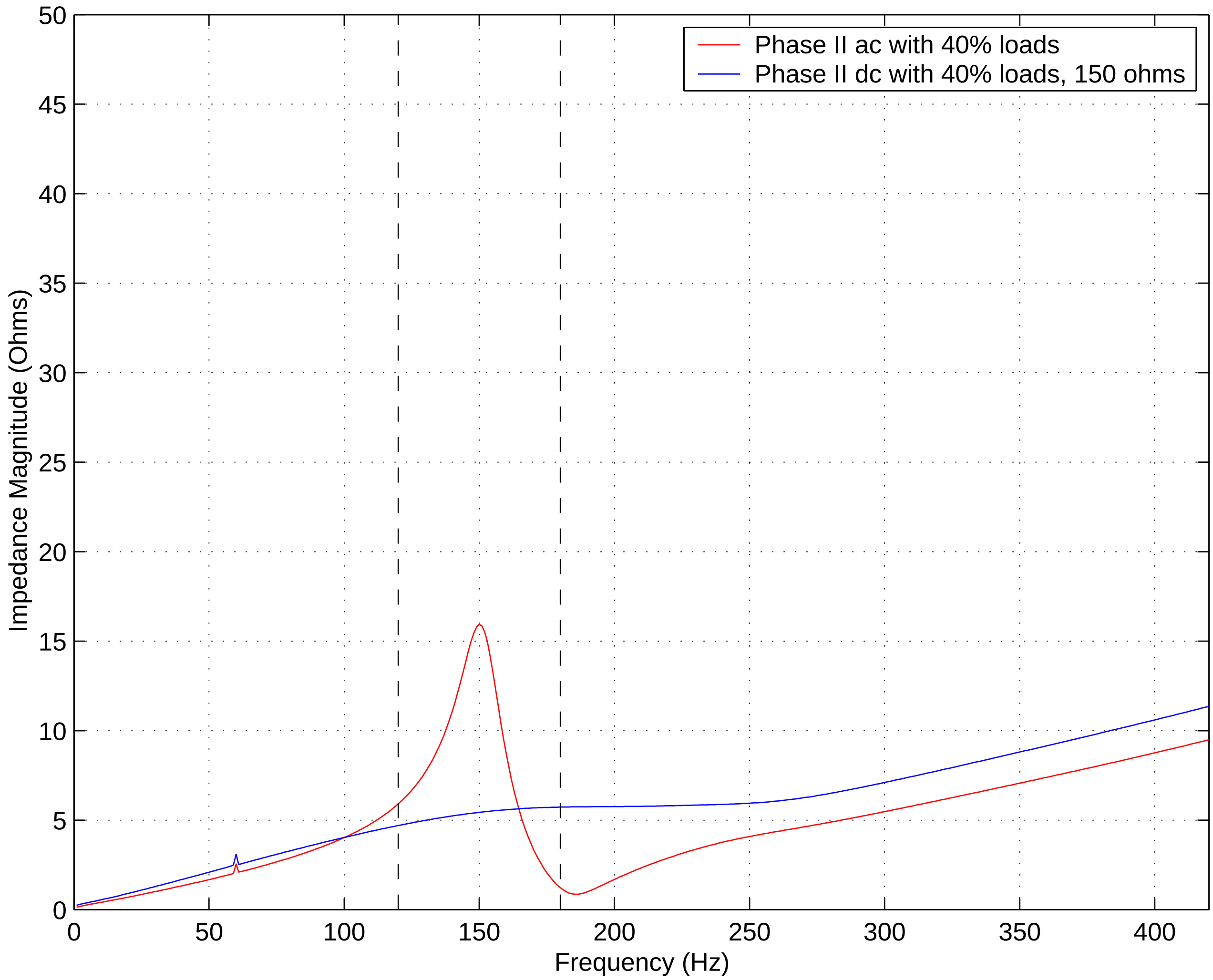


Figure D−188: Frequency Scan at Singer 345 kV − Cont 2
Phase II ac with 40% loads
Impedance Magnitude (Ohms)
Frequency (Hz)
0
20
40
60
80
100
120
140
160
180
200
0
50
100
150
200
250
300
350
400

Figure D−189: Frequency Scan at Pequonnock 115 kV − Cont 2



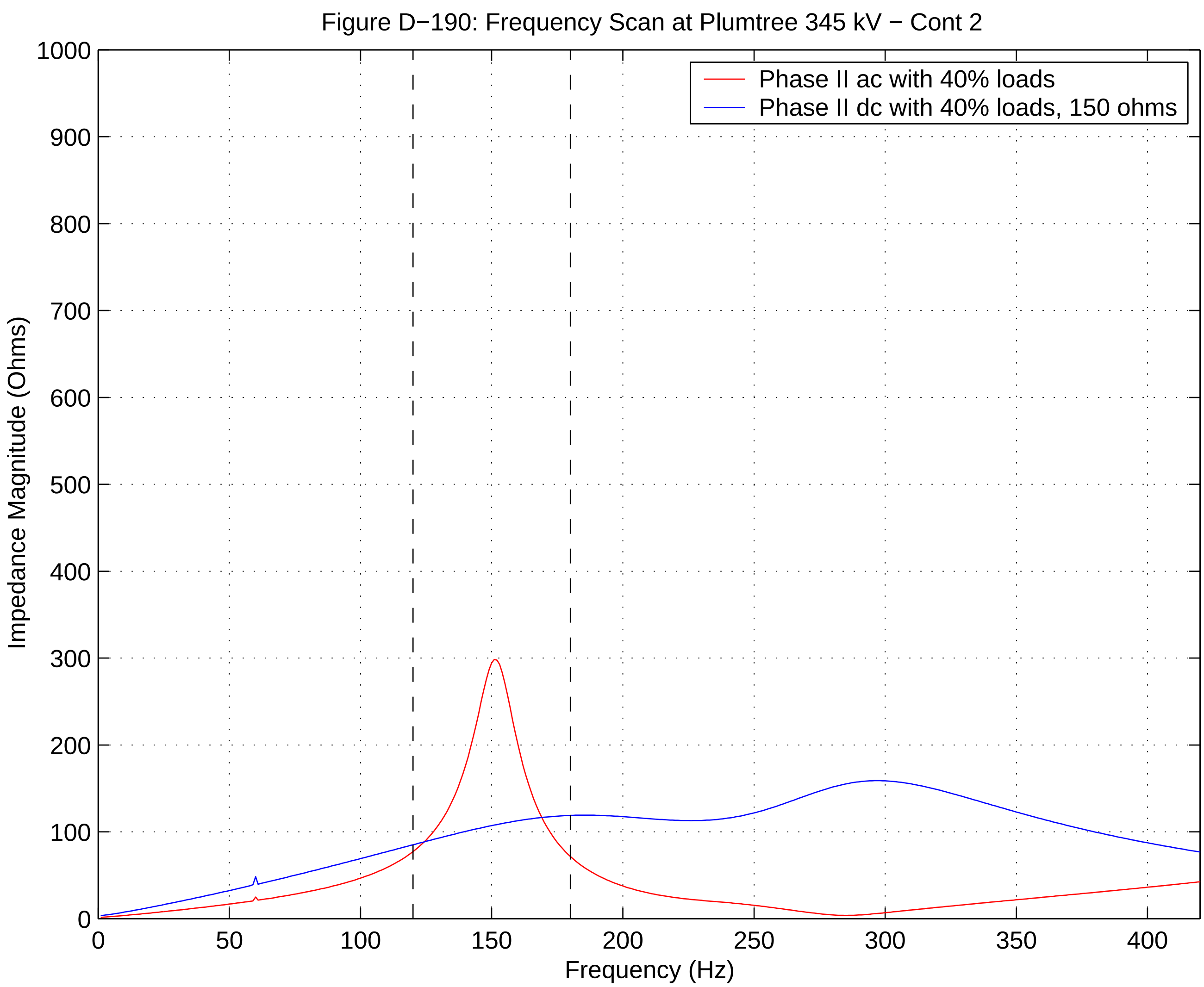


Figure D−190: Frequency Scan at Plumtree 345 kV − Cont 2
Phase II ac with 40% loads
Phase II dc with 40% loads, 150 ohms
Impedance Magnitude (Ohms)
Frequency (Hz)
0
100
200
300
400
500
600
700
800
900
1000
0
50
100
150
200
250
300
350
400

Figure D−191: Frequency Scan at Southington 345 kV − Cont 2

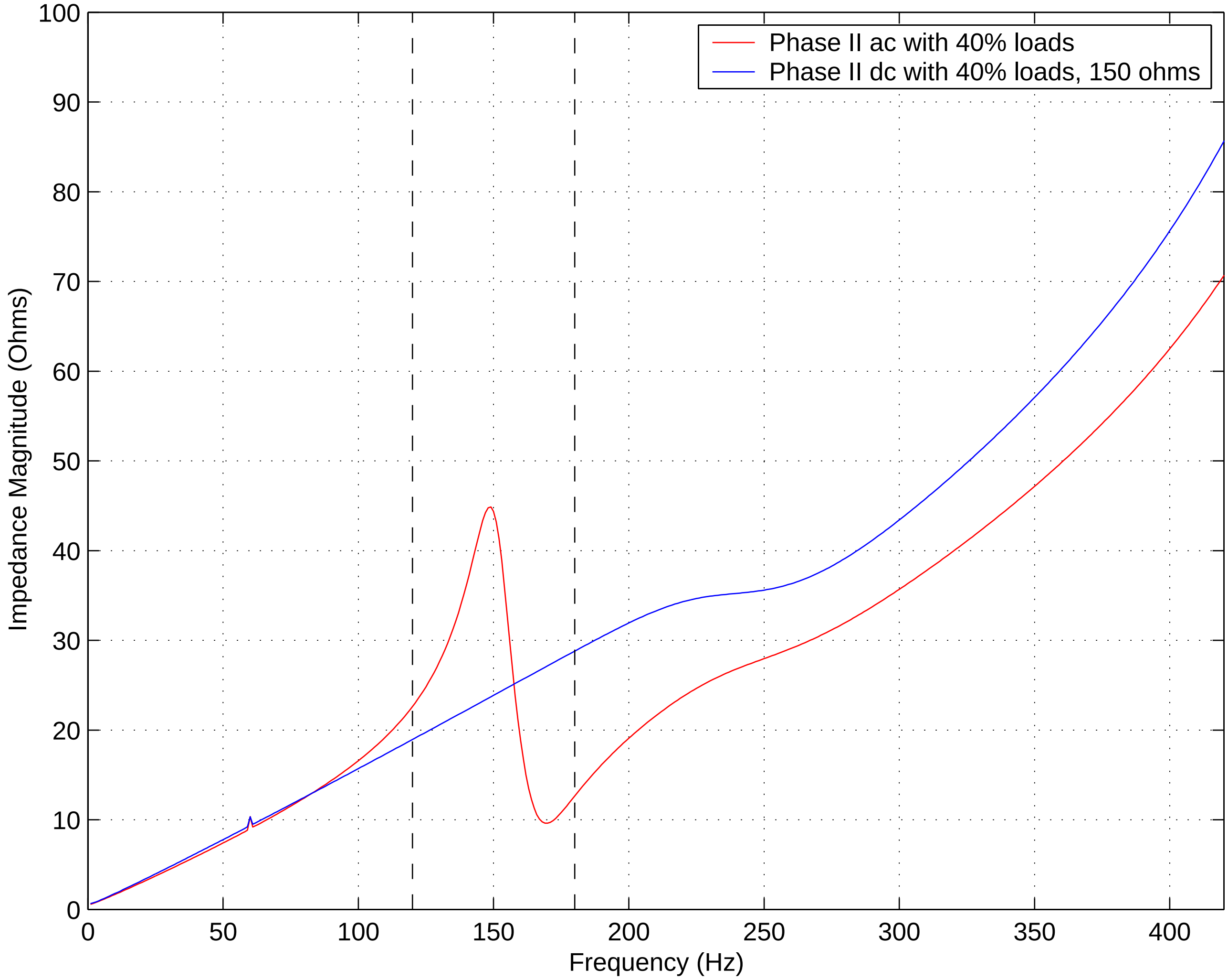
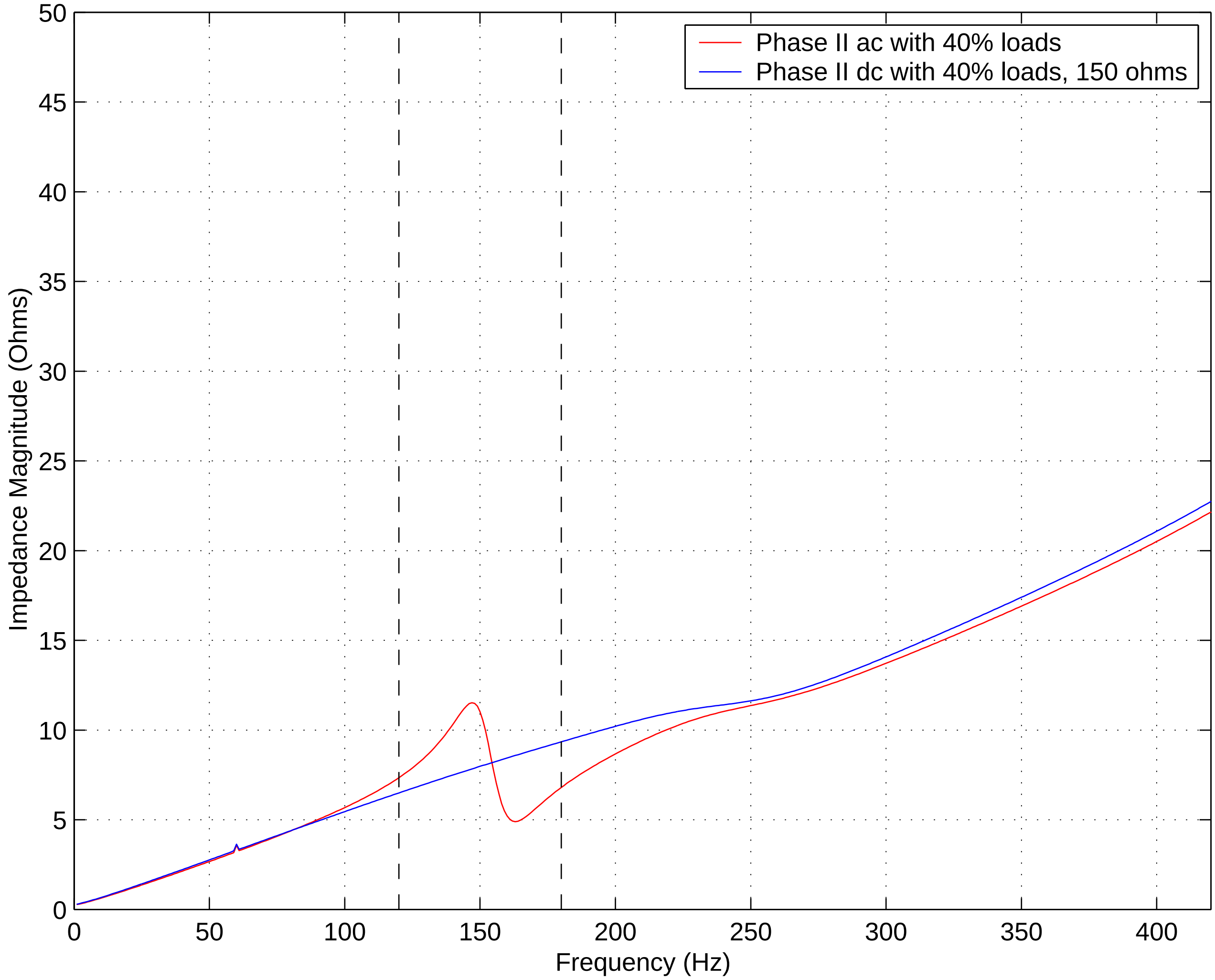


Figure D−192: Frequency Scan at Woodmont 115 kV − Cont 2



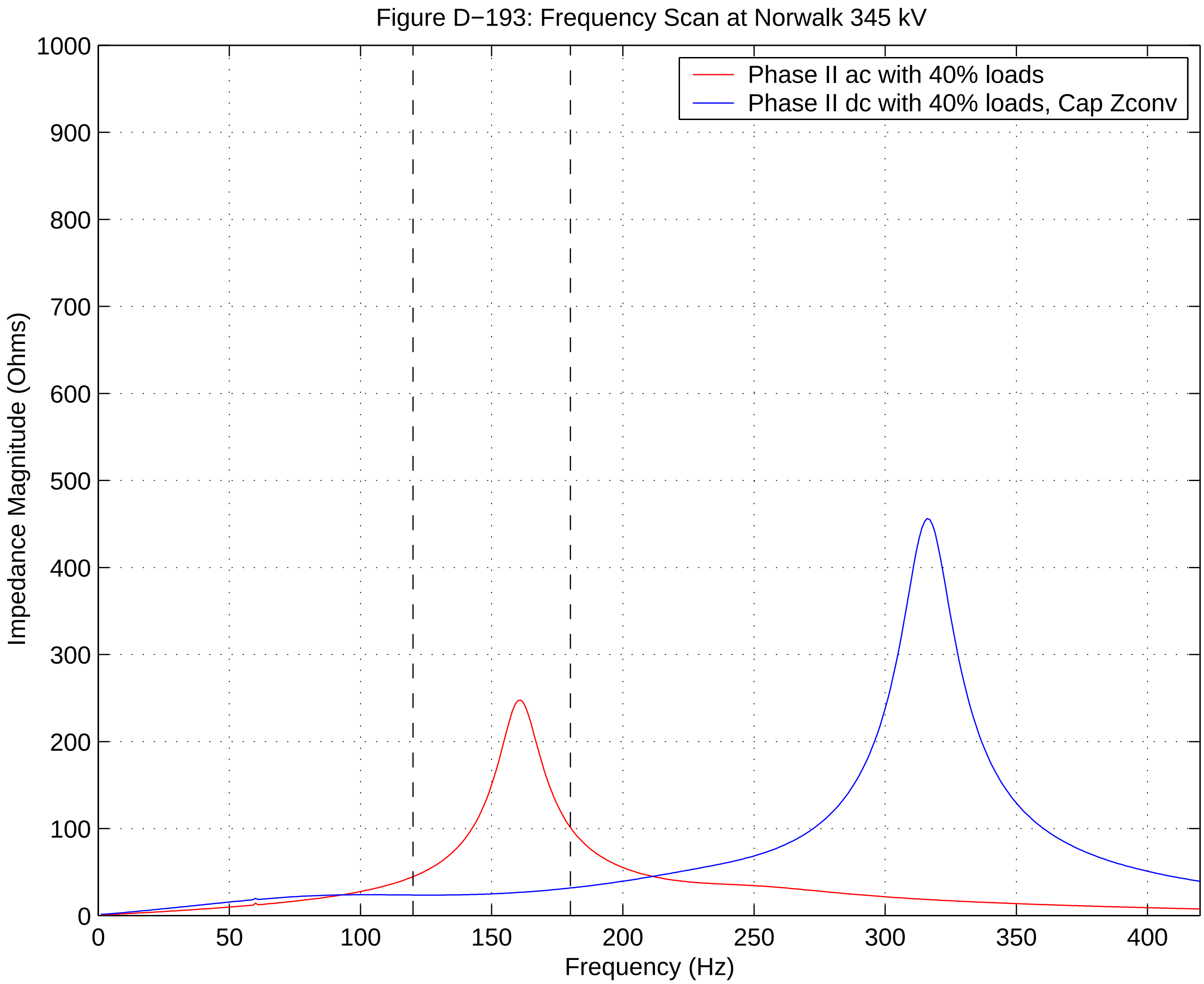


Figure D−193: Frequency Scan at Norwalk 345 kV
Phase II ac with 40% loads
Phase II dc with 40% loads, Cap Zconv
Impedance Magnitude (Ohms)
Frequency (Hz)
0
100
200
300
400
500
600
700
800
900
1000
0
50
100
150
200
250
300
350
400

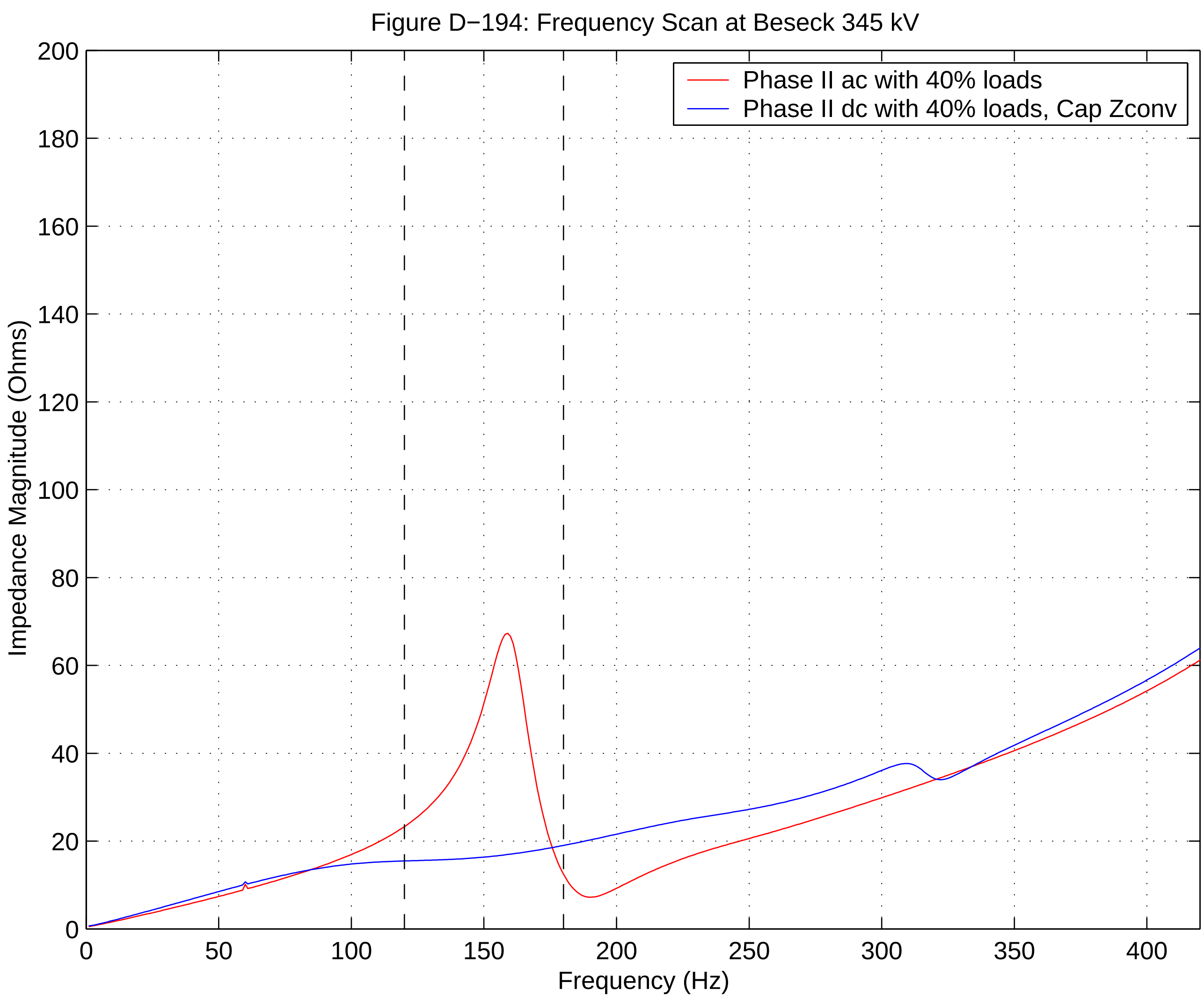
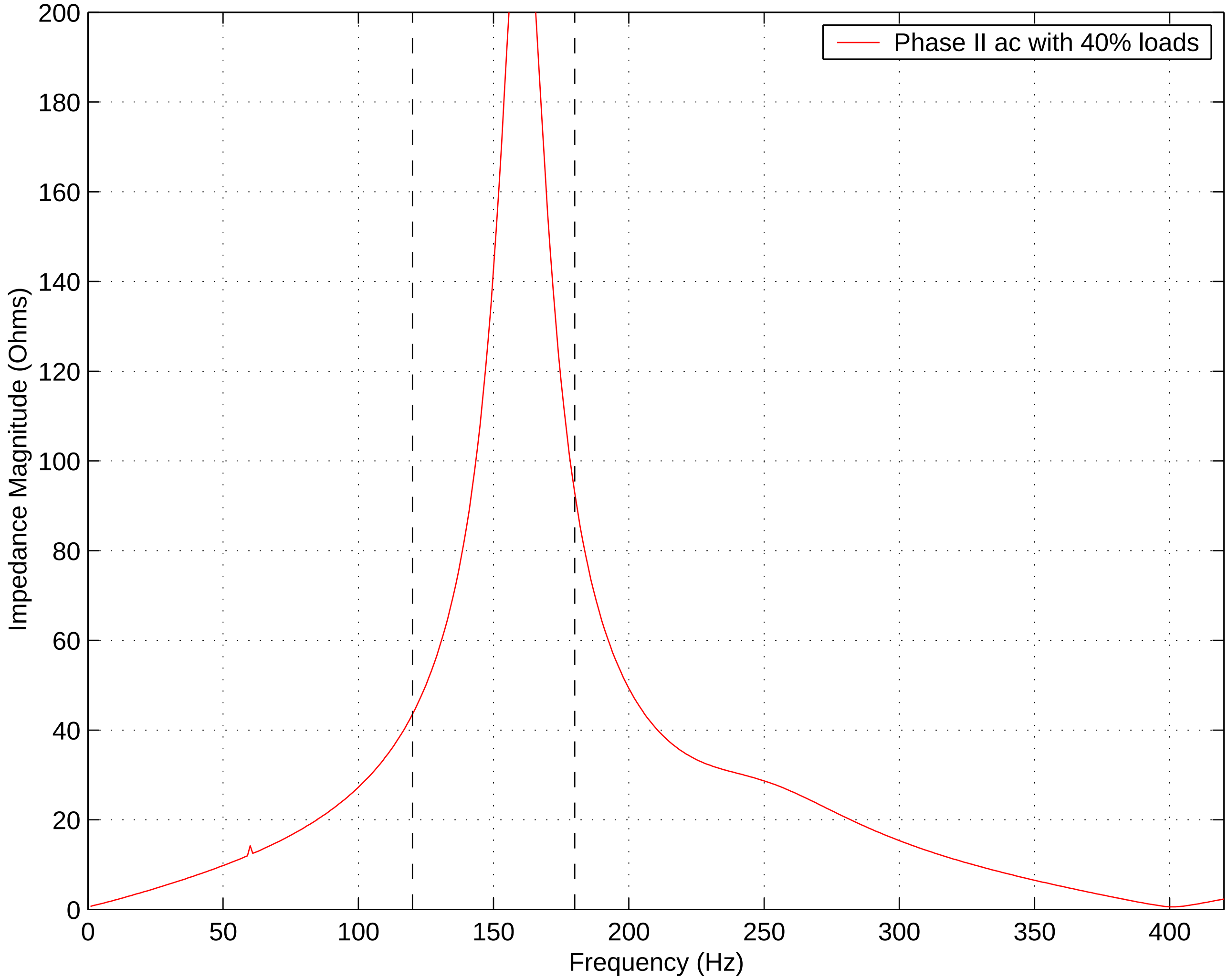


Figure D−194: Frequency Scan at Beseck 345 kV
Phase II ac with 40% loads
Phase II dc with 40% loads, Cap Zconv
Impedance Magnitude (Ohms)
Frequency (Hz)
0
20
40
60
80
100
120
140
160
180
200
0
50
100
150
200
250
300
350
400

Figure D−195: Frequency Scan at Devon 345 kV



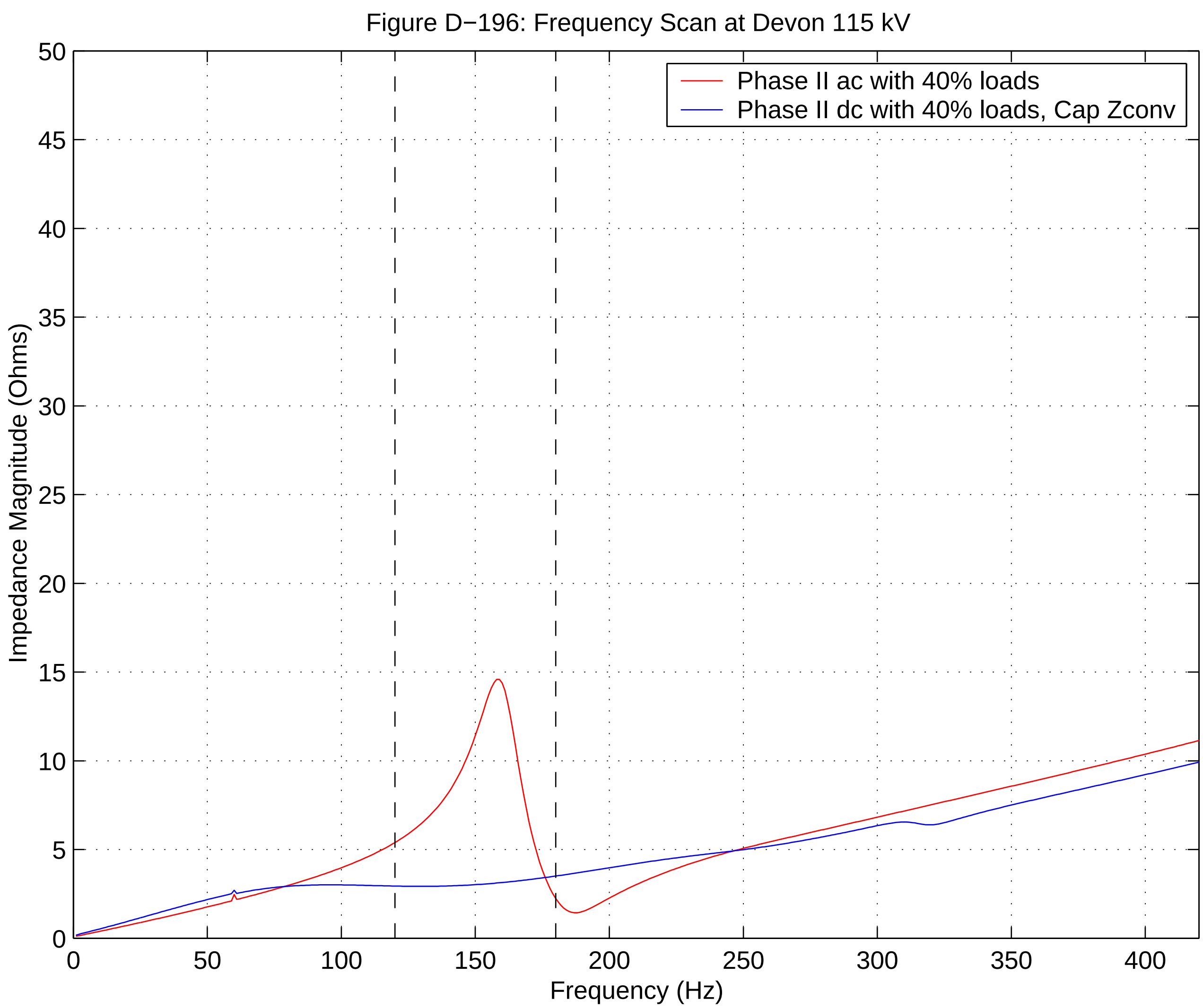


Figure D−196: Frequency Scan at Devon 115 kV
Phase II ac with 40% loads
Phase II dc with 40% loads, Cap Zconv
Impedance Magnitude (Ohms)
Frequency (Hz)
0
5
10
15
20
25
30
35
40
45
50
0
50
100
150
200
250
300
350
400

Figure D−197: Frequency Scan at Singer 345 kV

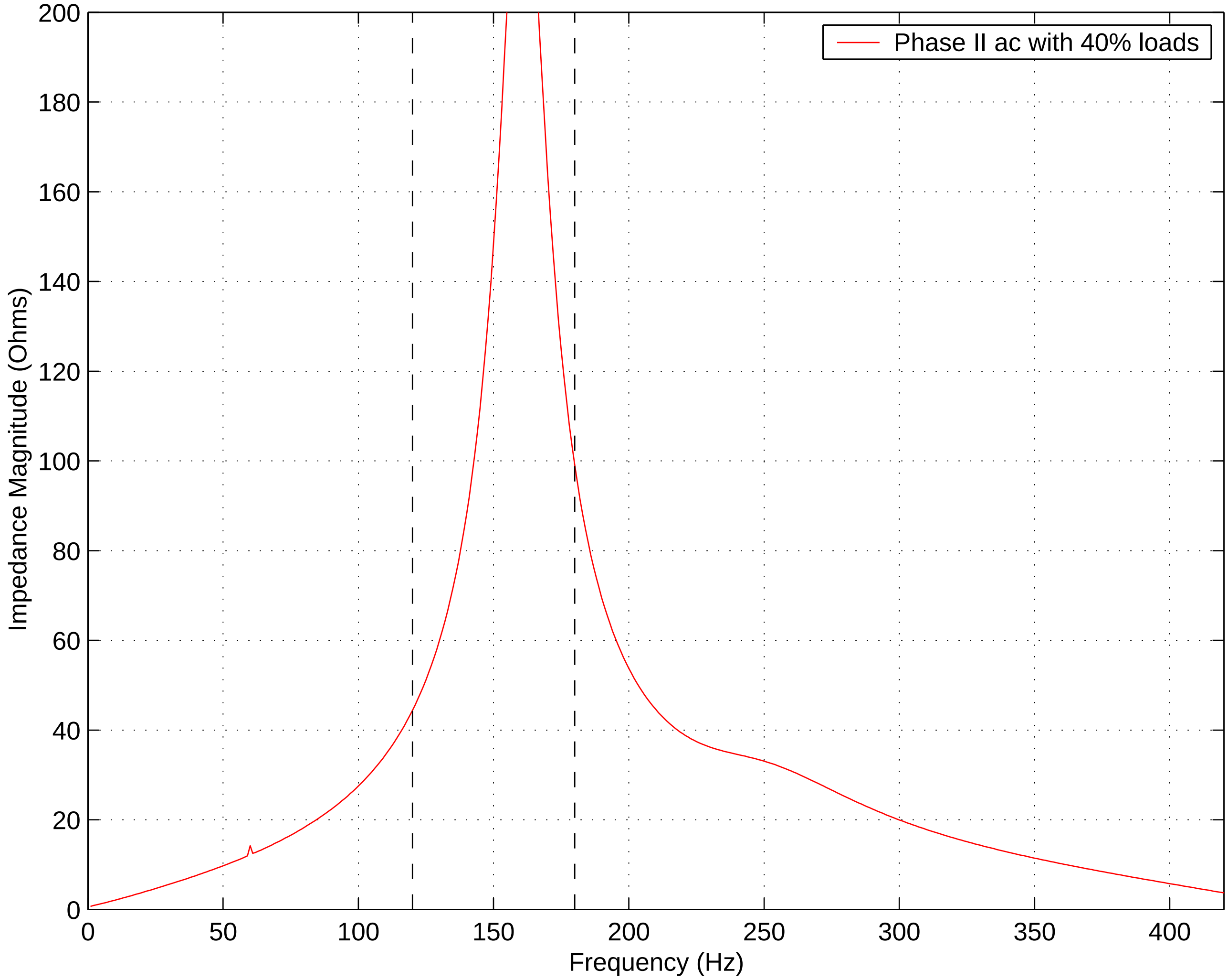
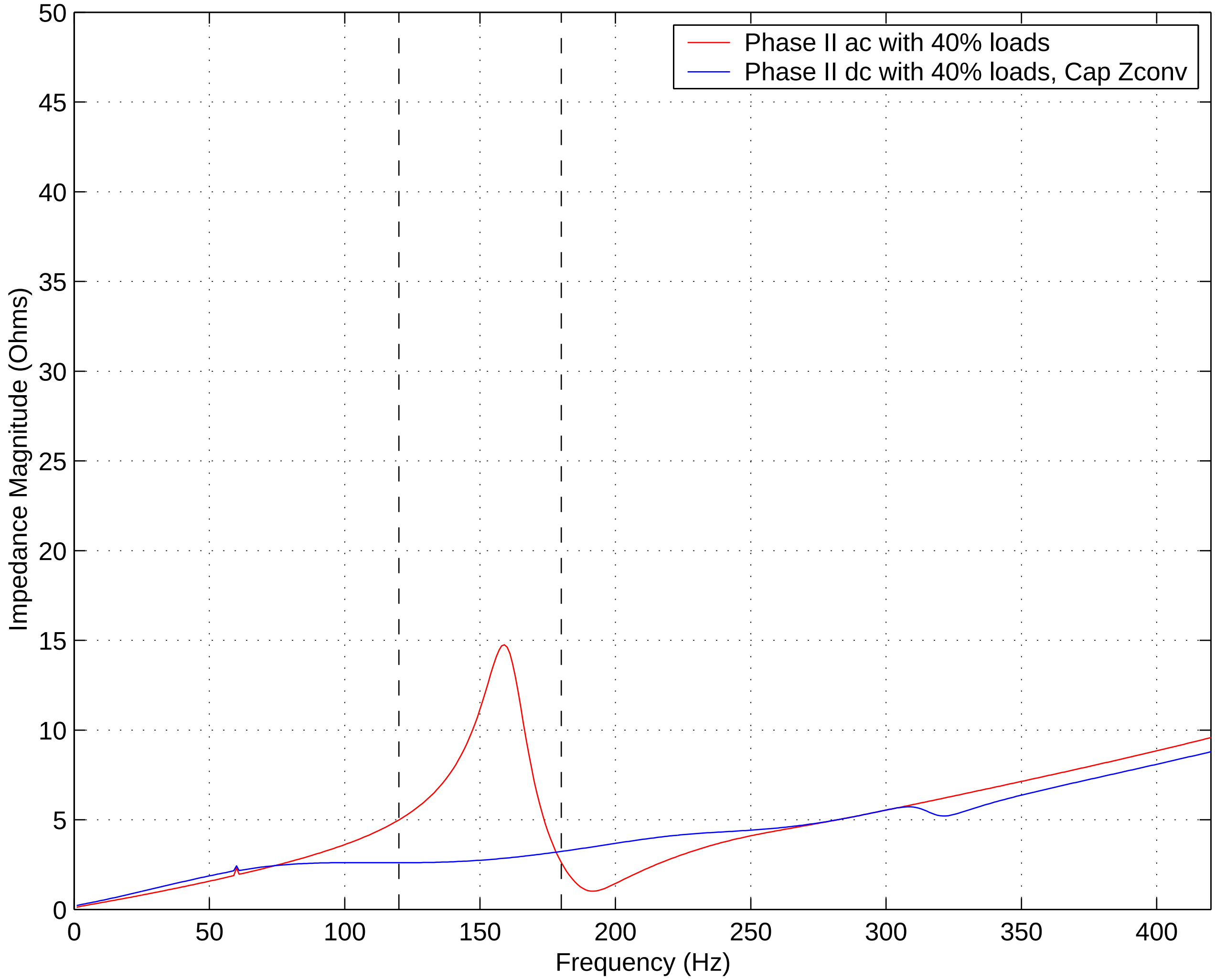


Figure D−198: Frequency Scan at Pequonnock 115 kV



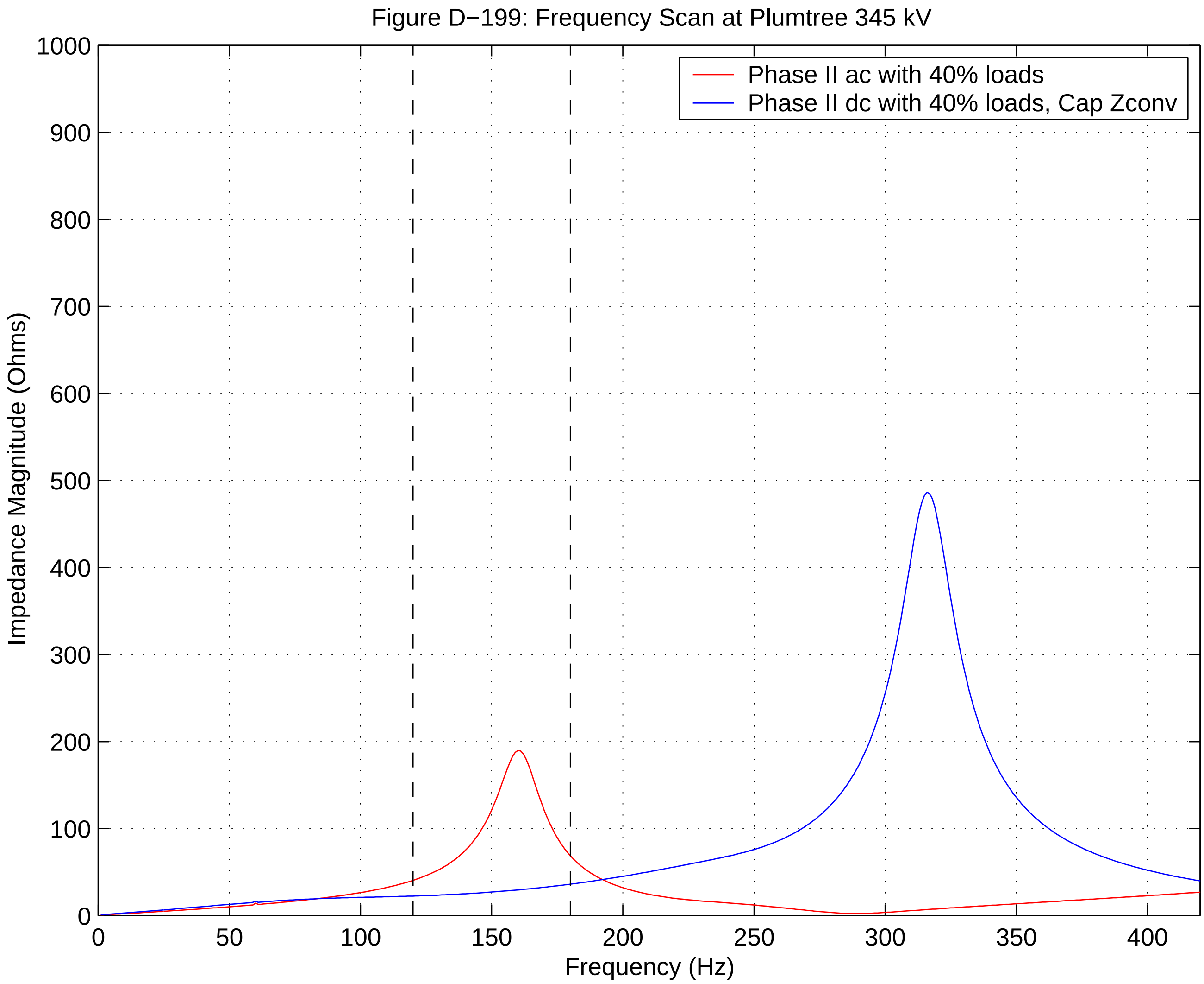
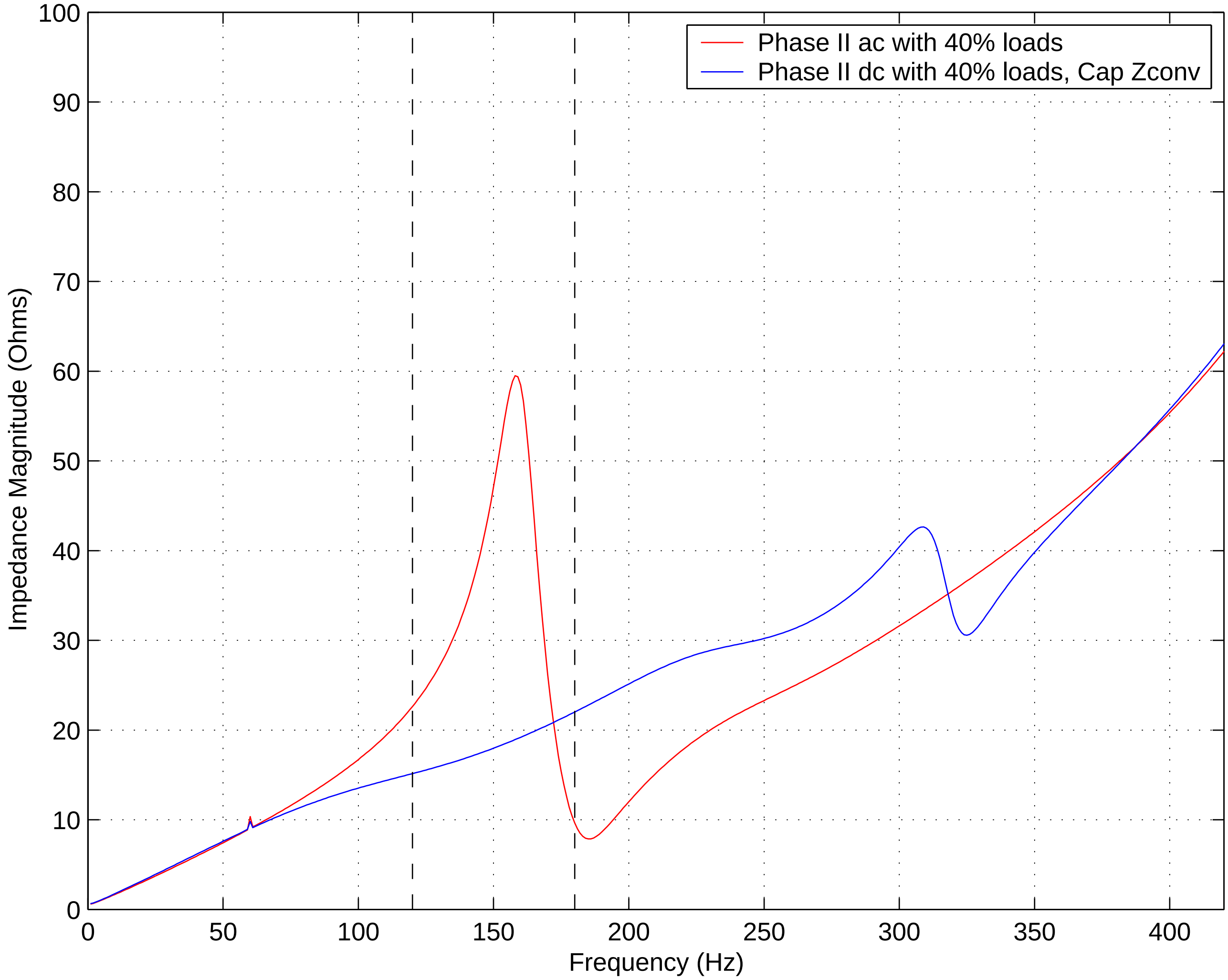


Figure D−199: Frequency Scan at Plumtree 345 kV
Phase II ac with 40% loads
Phase II dc with 40% loads, Cap Zconv
Impedance Magnitude (Ohms)
Frequency (Hz)
0
100
200
300
400
500
600
700
800
900
1000
0
50
100
150
200
250
300
350
400

Figure D−200: Frequency Scan at Southington 345 kV



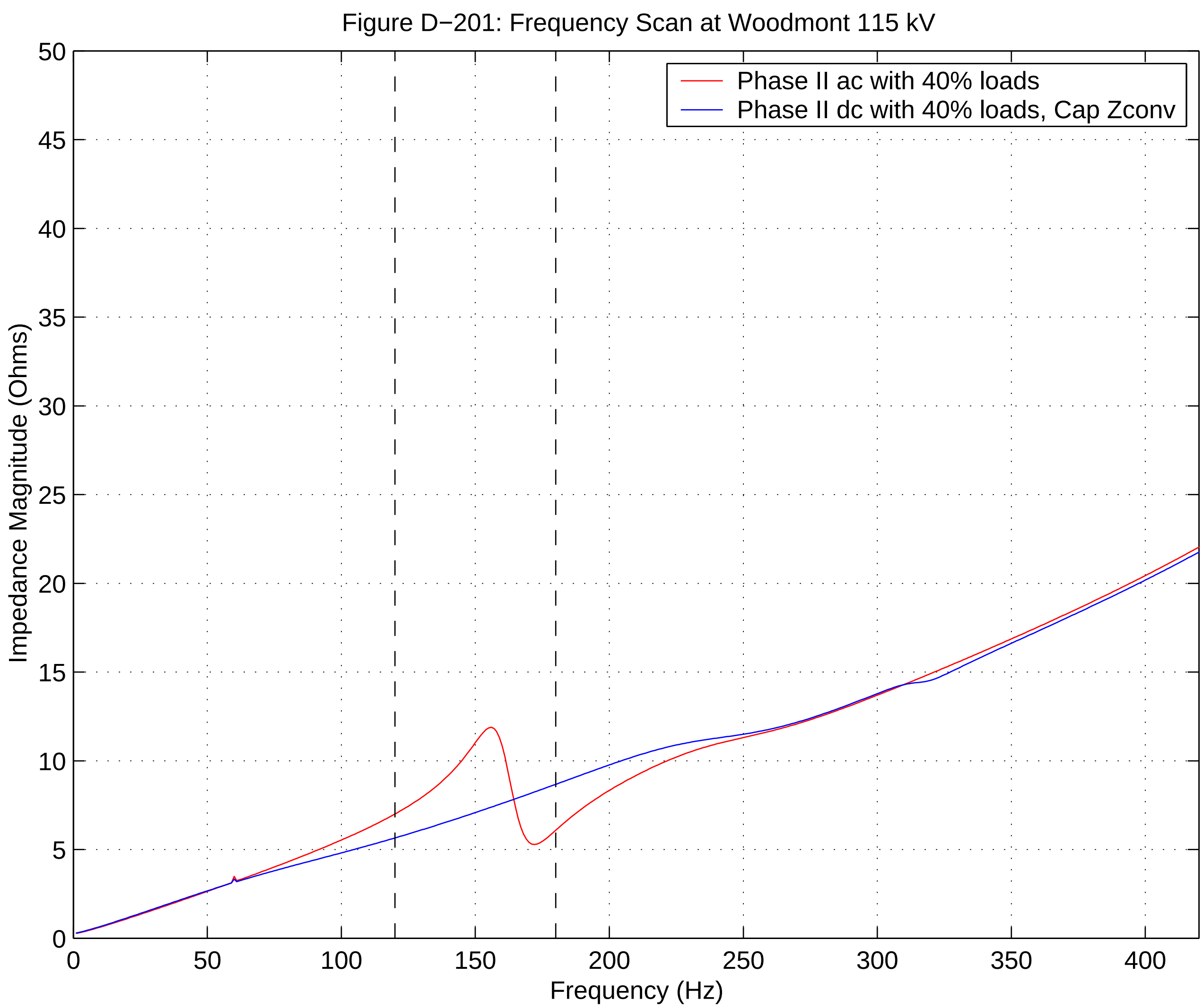


Figure D−201: Frequency Scan at Woodmont 115 kV
Phase II ac with 40% loads
Phase II dc with 40% loads, Cap Zconv
Impedance Magnitude (Ohms)
Frequency (Hz)
0
5
10
15
20
25
30
35
40
45
50
0
50
100
150
200
250
300
350
400

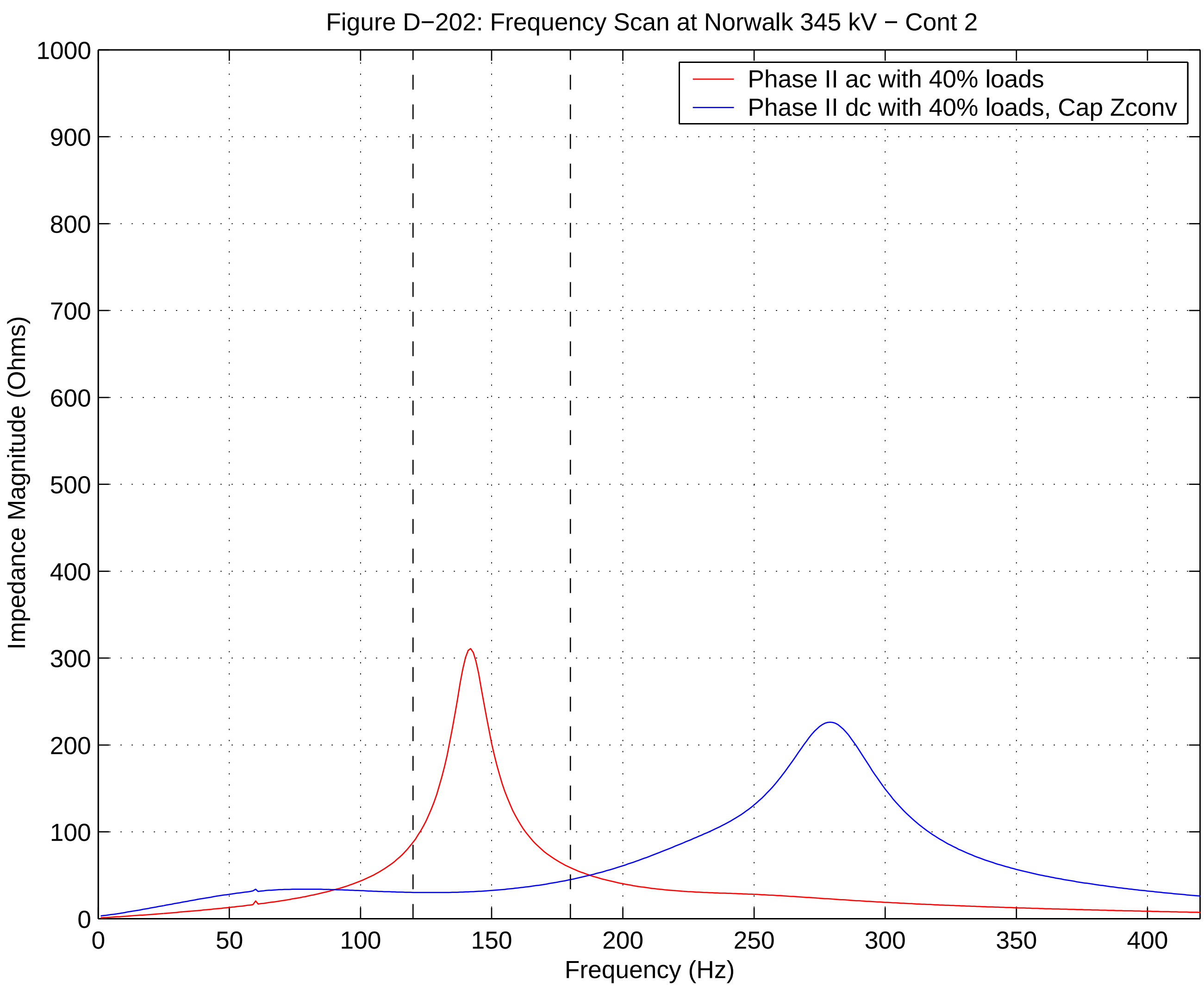
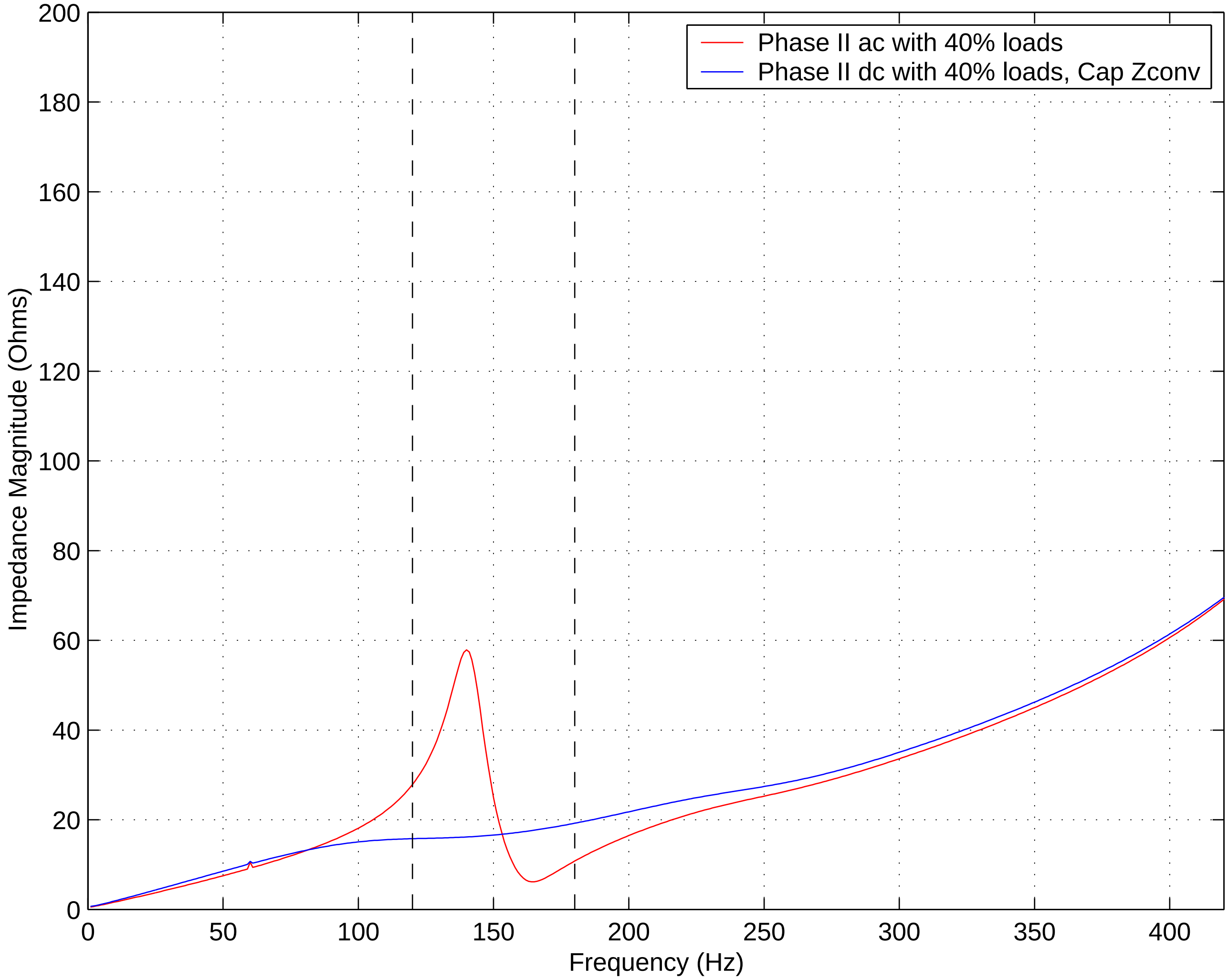


Figure D−202: Frequency Scan at Norwalk 345 kV − Cont 2
Phase II ac with 40% loads
Phase II dc with 40% loads, Cap Zconv
Impedance Magnitude (Ohms)
Frequency (Hz)
0
100
200
300
400
500
600
700
800
900
1000
0
50
100
150
200
250
300
350
400

Figure D−203: Frequency Scan at Beseck 345 kV − Cont 2



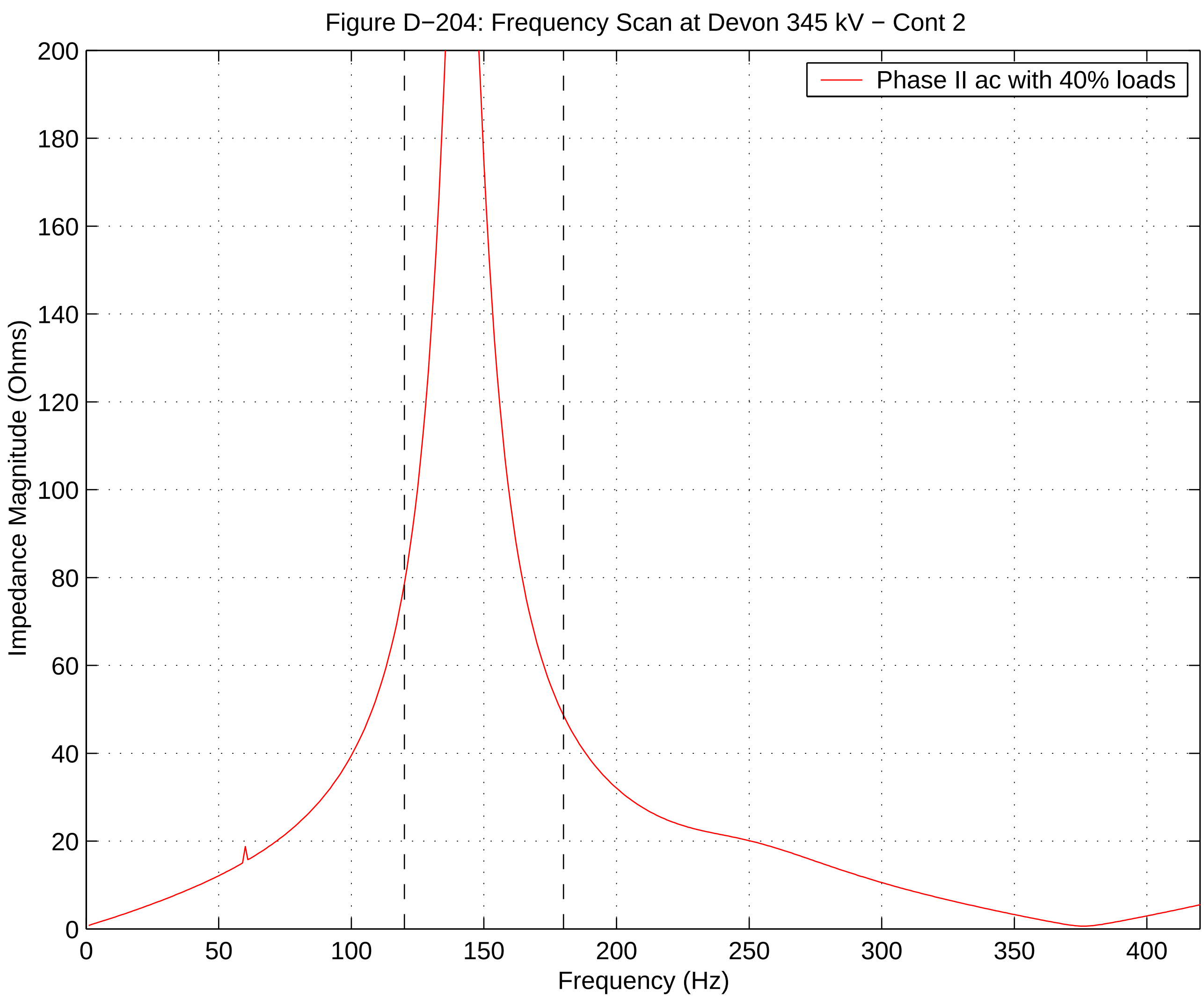
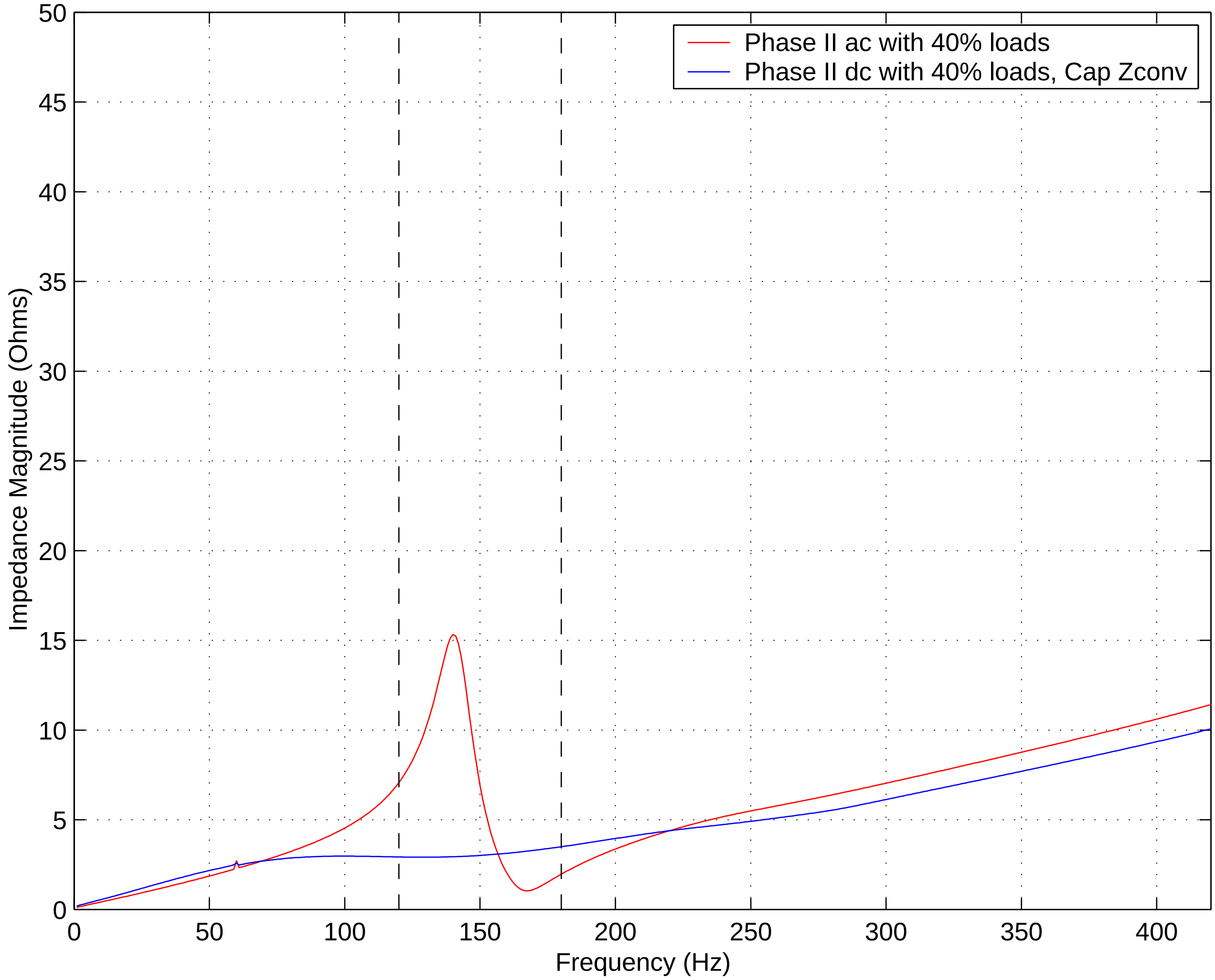


Figure D−204: Frequency Scan at Devon 345 kV − Cont 2
Phase II ac with 40% loads
Impedance Magnitude (Ohms)
Frequency (Hz)
0
20
40
60
80
100
120
140
160
180
200
0
50
100
150
200
250
300
350
400

Figure D−205: Frequency Scan at Devon 115 kV − Cont 2



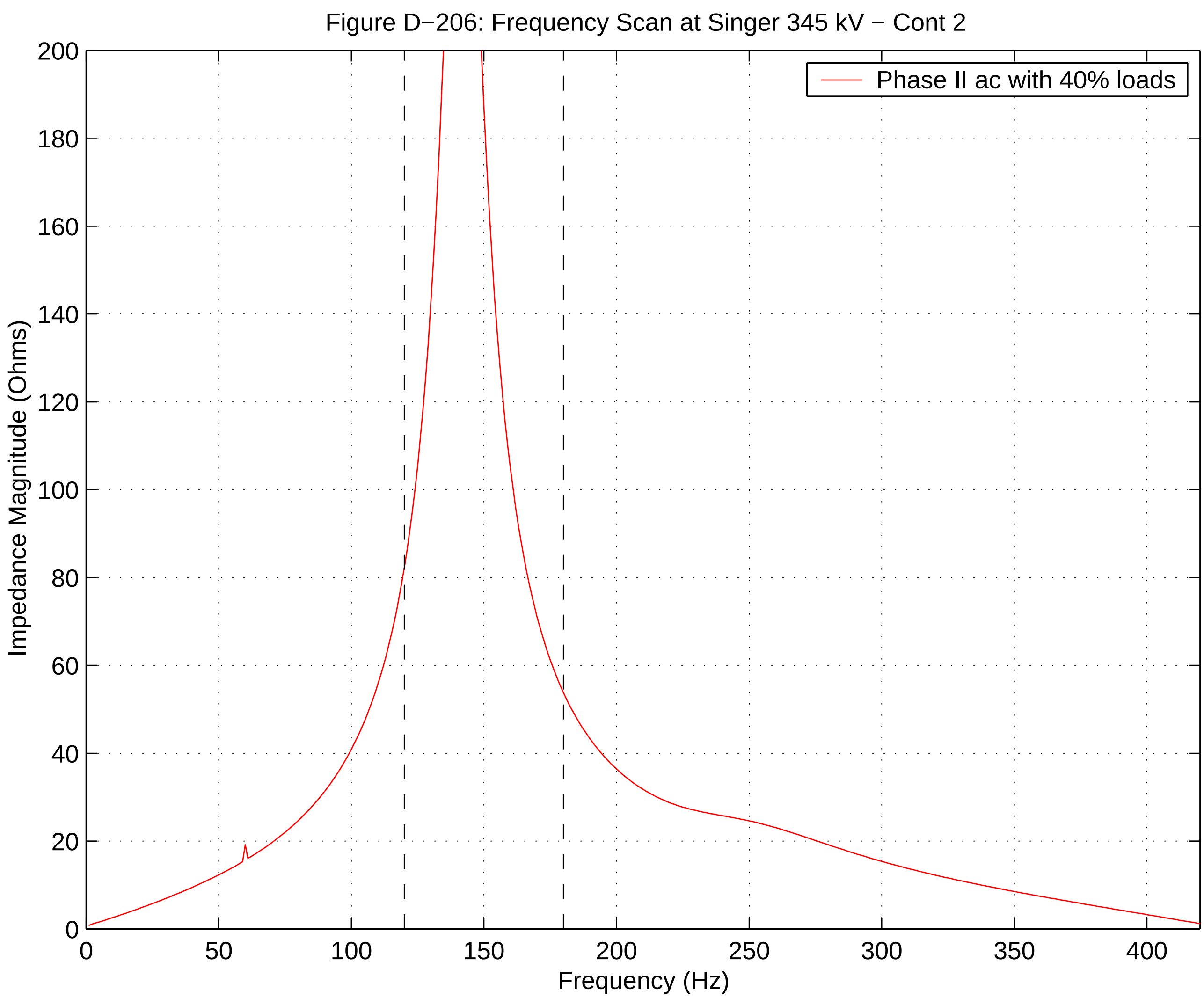
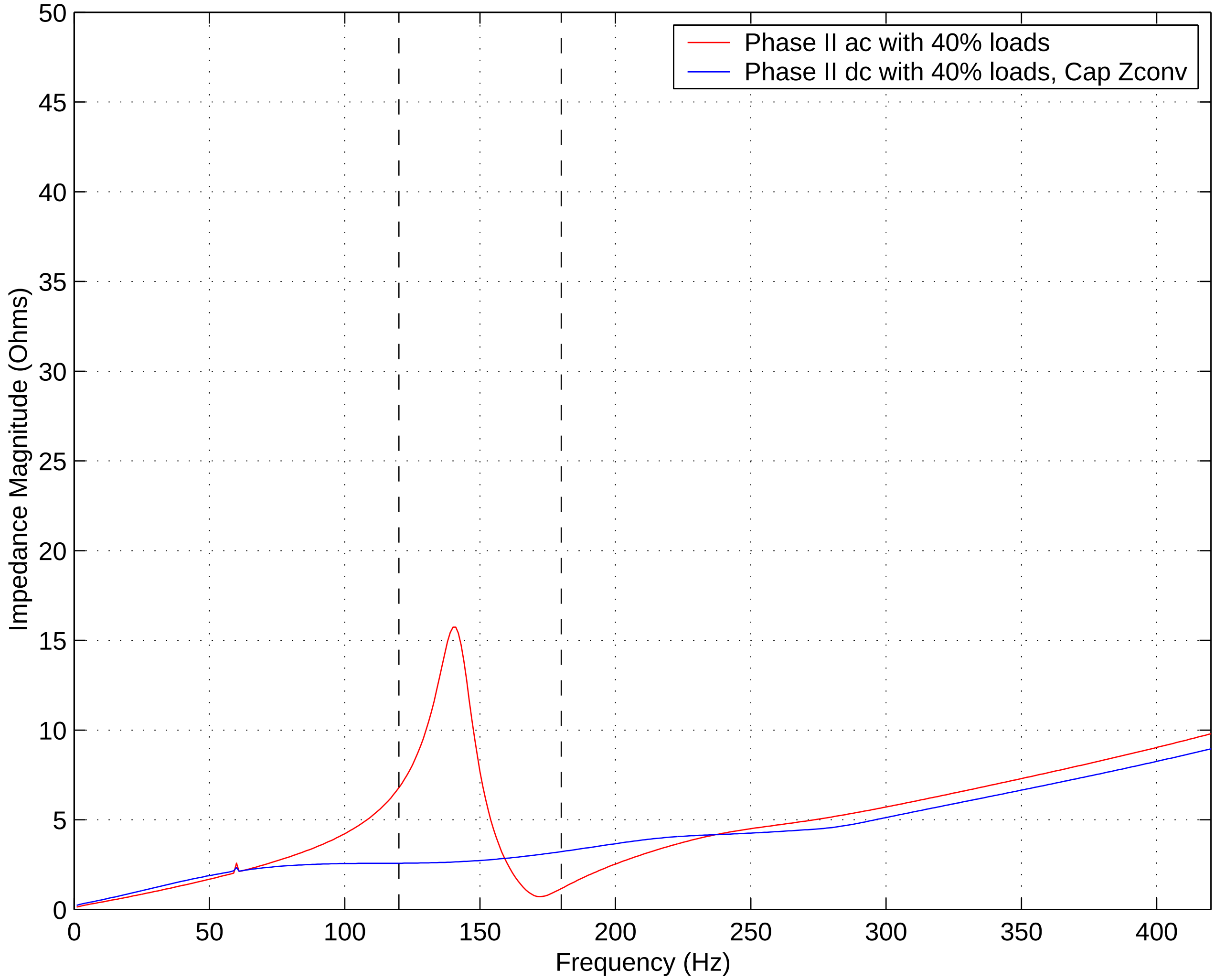


Figure D−206: Frequency Scan at Singer 345 kV − Cont 2
Phase II ac with 40% loads
Impedance Magnitude (Ohms)
Frequency (Hz)
0
20
40
60
80
100
120
140
160
180
200
0
50
100
150
200
250
300
350
400

Figure D−207: Frequency Scan at Pequonnock 115 kV − Cont 2



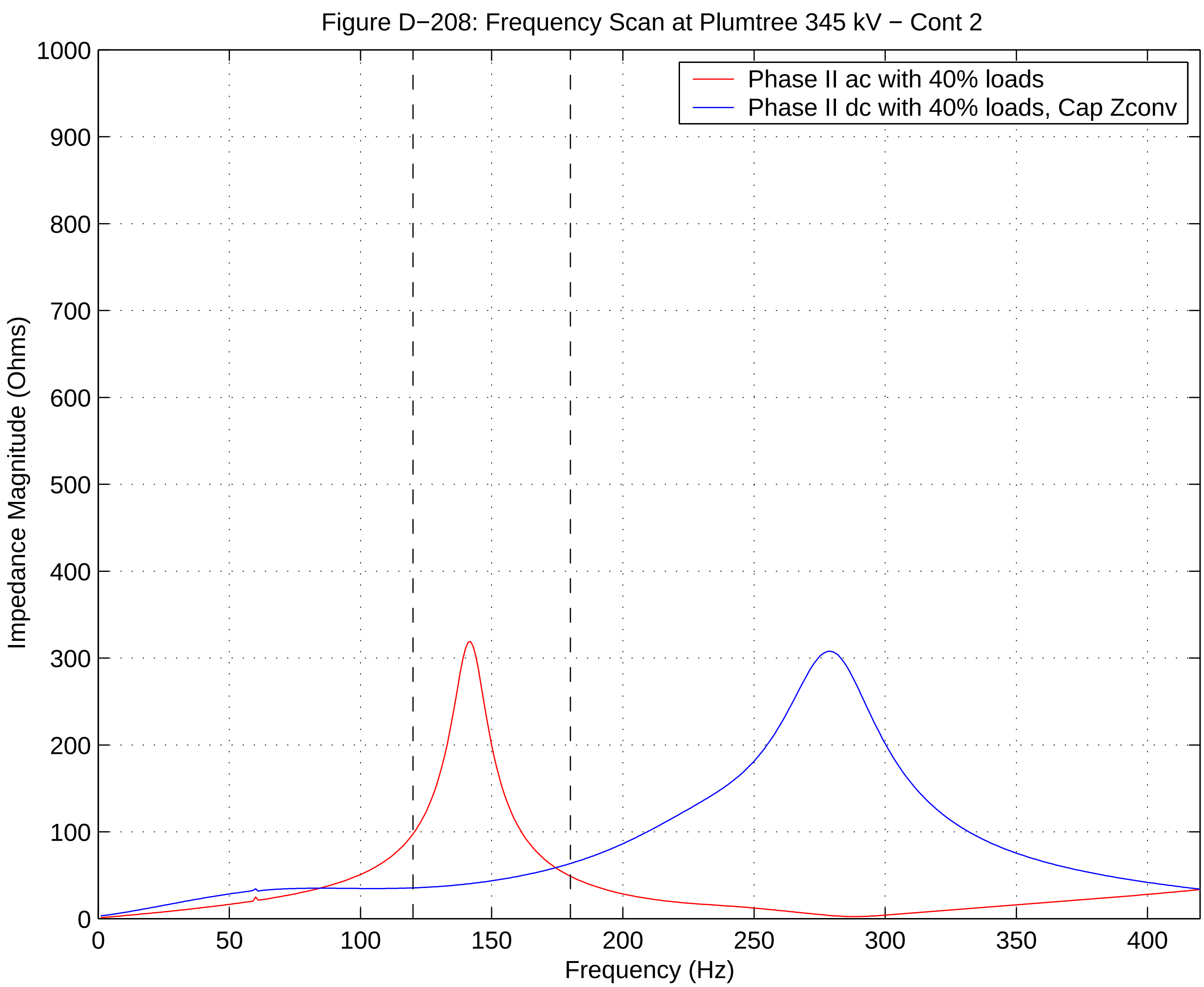


Figure D−208: Frequency Scan at Plumtree 345 kV − Cont 2
Phase II ac with 40% loads
Phase II dc with 40% loads, Cap Zconv
Impedance Magnitude (Ohms)
Frequency (Hz)
0
100
200
300
400
500
600
700
800
900
1000
0
50
100
150
200
250
300
350
400

Figure D−209: Frequency Scan at Southington 345 kV − Cont 2

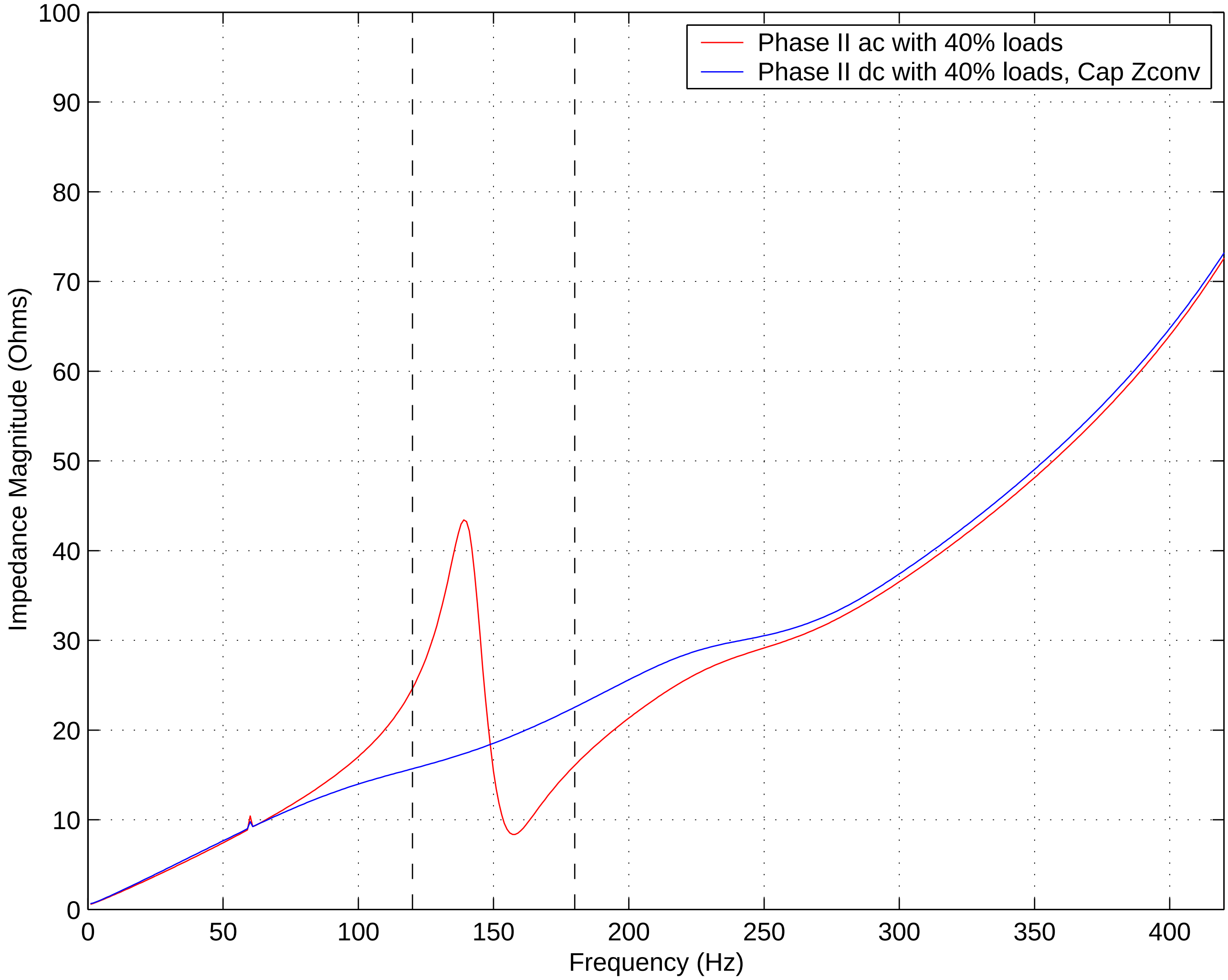


Figure D−210: Frequency Scan at Woodmont 115 kV − Cont 2