A Reduced Order Model for a TOV Study in a Solar PV Project

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***Abstract*—Special system studies are needed to assess the different preliminary designs of solar photovoltaic (PV) projects. One of these is a Temporary Overvoltage (TOV) study. The main purpose of a TOV study is to evaluate the capability of the surge arresters (SAs) within the substation. To assess the capability of the SAs accurately, a detailed electromagnetic transient (EMT) model of the project has to be built. With the detailed EMT model, which has a large number of inverters, the run time of the model becomes prohibitive even for a single scenario. In this paper, we propose a method to systematically reduce the order of the EMT model at the substation level thus making the model suitable for TOV studies. The response of the reduced order model is then benchmarked against the response of the full order model of an 80 MW solar PV project for various TOV scenarios. Simulation results show satisfactory agreement between the response of the detailed model and the response of the reduced order model. Additionally, the run time of the proposed reduced order model is less than the run time of the full order model by a factor of ninety six.**

I. Introduction

With the increased penetration of renewable energy into the grid, special system studies are called upon to assess their impact on various aspects of the power system. One of these aspects is evaluating the adequacy the of surge arresters within the substation. Surge arrester MCOV and energy handling capability are generally selected on an ad hoc manner in the early design stage. Assessment of the adequacy of the SAs in the substation ensures that SAs can ride through the TOV by absorbing an amount of energy that is within their energy handling capability and that the TOV level is limited to a value determined by applicable standards. The IEEE Standard C62.82.1-2010 [1] defines TOV as “an oscillatory phase-to-ground or phase-to-phase overvoltage that is at a given location of relatively long duration (seconds, even minutes) and that is undamped or only weakly damped; resulting from operation of a switching device or fault condition”.

This can occur when the PV inverter is suddenly disconnected from the grid. Because inverters act as a constant current source, hence when a circuit breaker opens the inverter terminal voltage can cause voltage fluctuations. When this occurs, inverters quickly shut down, but there can be a short period of time where some inverters can create overvoltage spikes. This is a concern for PV system owners and utilities since large voltage spikes can damage other equipment that is still connected in the vicinity.

Historically, assessment of SAs had been done under specific assumptions about the nature of TOV. For example, in conventional gas generation and if the neutral of synchronous generator is ungrounded, it is known that a single line to ground fault can cause the phase to ground voltage to increase by a factor of $\sqrt{3}$. This value can be used along with the surge arrester TOV withstand capability curve [2] to judge the adequacy of the SA. However, due to the nature of the technology used in renewable energy resources, this might not be true. Renewable energy resources are generally inverter based generation. These inverters incorporate a large number of switches and are of various topologies. The temporary overvoltage withstand capability is usable for TOVs lasting at least 10 milliseconds and due to the microprocessor controller used within these inverters, most TOV events are transient in nature and the duration of the TOV events in most cases do not exceed milliseconds. Thus, the SA overvoltage withstand capability curve is of no practical usefulness in case of TOV events due to inverter based technologies. Hence, it is not always possible to assess the capability of a SA using the project configuration, grounding scheme and the TOV withstand capability.

This necessitates a paradigm shift in performing TOV studies. Building the renewable energy project in an EMT type software becomes a must to assess the performance of SAs under various scenarios. The model must include all inverters as well as all SAs characteristics in order to accurately represent the project. Running such models in EMT software requires small solution time step and thus a long simulation run time. Moreover, performing many TOV scenarios becomes a daunting task due to the long simulation run time. Thus, it is of utmost importance to develop a method to reduce the total number of switches (inverters) in the model to reduce the simulation run time.

Most equivalencing techniques [3] treat the renewable project as one unit, i.e., the whole project starting from the main power transformer (MPT) down to the medium voltage collector system and the low voltage inverters are replaced by a single electrical component that accurately captures the transient performance of the project as a whole. This is done mainly for grid impact studies and specifically for dynamic simulations. Popular methods such as the one in [4] is suitable only for power flow and dynamic studies not EMT type simulations.

In this paper, we provide a way to reduce the order of the solar PV project at the substation level. Each feeder of the collector system is reduced on its own to a simple generation resource and an impedance. Thus the number of the inverters in the EMT model is drastically reduced to the number of the feeders in the collector system. It thus possible to study the performance of the SAs in the substation since they, generally, are installed at the beginning of each of these collector feeders.

The paper is organized as follows. The detailed system EMT model is described in section §II. The benchmark response of the inverter as supplied by the manufacturer is shown in III. The methodology is provided in section §IV. The TOV scenarios used for comparing the detailed and reduced order model is provided in section §V. The results of the reduced order model is shown in section §VI. Conclusions are summarized in section §VII.

II. Detailed System Model

The system under study is an 80 MW solar PV project and is shown in figure 1. The project is divided into four collector feeders and two capacitor banks each rated at 4.5 MVAr. Each feeder has different number of inverters connected to it. The configuration of each feeder has been removed from the paper for confidentiality reasons.

The number of inverters on each feeder is shown in figure 1. The project has a total of 45 inverters and each one is capable of producing 1.8 MVA. Each inverter block in figure 1 has a DC to AC stage, an LC filter and an inverter step up transformer (ISU) transformer. Each ISU transformer is rated at 1.85 MVA and connected in delta-star with the star connected to the low voltage side of the inverter and ungrounded. The low voltage is 0.42 kV while the medium voltage is 34.5 kV. A schematic of the inverter is shown in figure 2.

Surge Arresters exist at the beginning of each feeder inside the substation as shown in figure 1. All surge arresters at the medium voltage level are MOV type, have the same MCOV of 24.4 kV and have the same energy handling capability of 219 kJ. The V-I characteristics of the SAs are obtained from [5] and is shown in figure 3. The project connects to the Point of Interconnection (POI) at 138 kV thorough the MPT which has rating of 89 MVA. The feeder circuit breakers are EMA type breakers [6]. These circuit breakers are equipped with a mechanically interlocked switch on the load side that grounds the load side within 1 cycle of opening the circuit breaker's main contacts.

III. Inverter Benchmark Tests

As has been stated in section §I, the inverter response in fundamentally different from conventional synchronous machines. To be able to successfully reduce the order of the model and design the benchmark scenarios in section §V, the response of the inverter under specific tests has to be known.

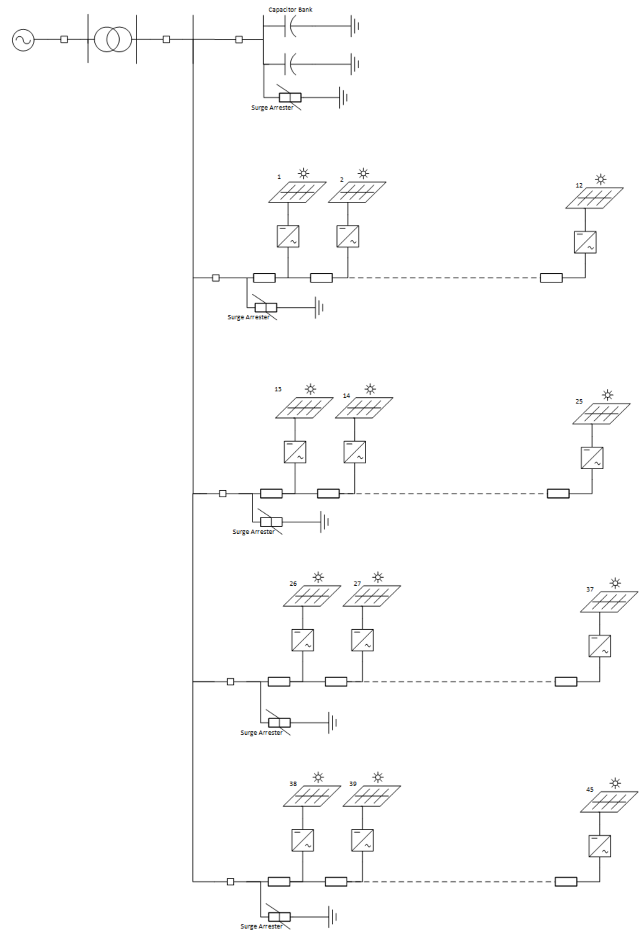

Fig. 1. Full Order EMT model

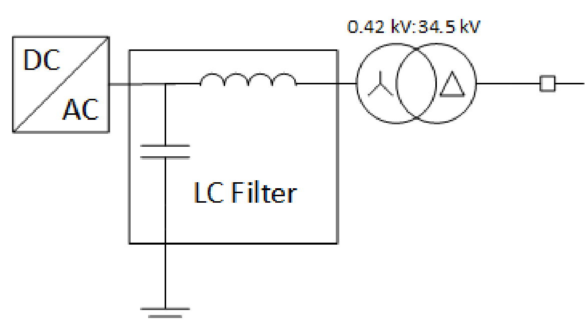

Fig. 2. Schematic of the inverter in the project

The inverter manufacturer supplied two benchmark tests. The first one is a load rejection test in figure 4 and the second one is a line to line fault in figure 5. The fault is performed at the inverter terminals with the ISU transformer terminals connected to a infinite bus. It can be seen from both figure 4 and figure 5 that the load rejection test produces the worst TOV as opposed to conventional power systems where generally the single line to ground fault causes the highest TOV.

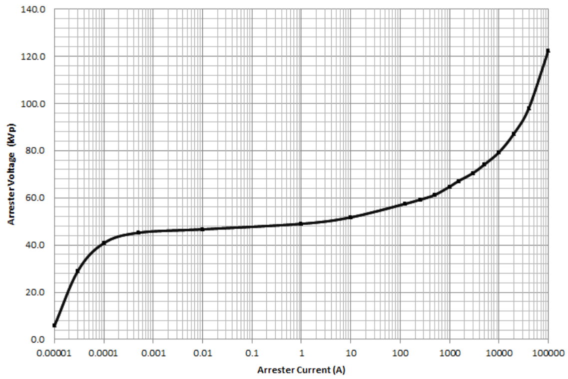

Fig. 3. Voltage-Current (V-I) Characteristics of the MV surge arrester

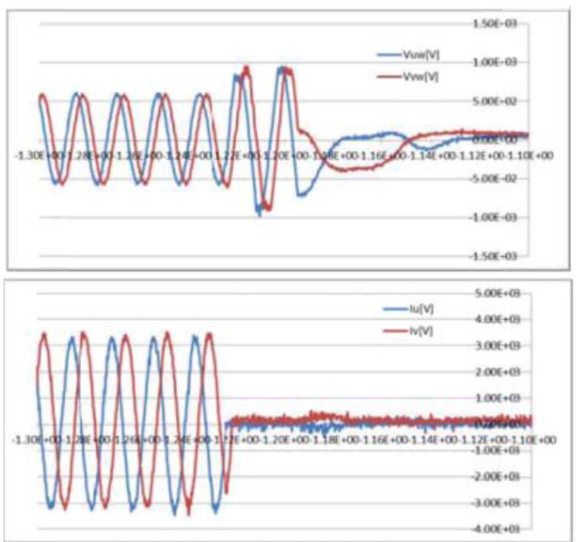

Fig. 4. Load rejection test (upper curve is voltage - lower curve is current)

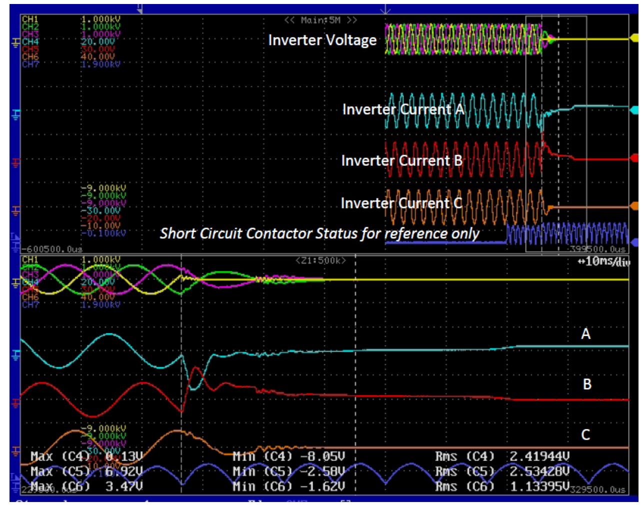

Fig. 5. Phase A to Phase B fault on the inverter terminal

IV. Methodology

Just as any electrical source can be represent by its Thevenin's or Norton's equivalent [7], [8], the inverters within the solar PV project can be modeled as such depending on the technology used within the inverter. However, most manufacturers of solar PV inverters use a technology that makes the inverters act as a current source or a voltage controlled current source. Due to that, Norton's equivalent model would be most suitable. A Norton's equivalent consists of two parts: the Norton's current source and the impedance in parallel with it.

The basic idea behind the method in this paper is to represent each feeder by a pseudo-Norton's equivalent. The pseudo-Norton's equivalent will consist of two parts: a pseudo-Norton source and an impedance in parallel. The pseudo-Norton's source will be responsible for equivalencing the low frequency response of the feeder, while the impedance in parallel will be equivalencing the high frequency response of the feeder. This effectively means that the step response of the pseudo-Norton's source should correspond to the low frequency response portion of the overall feeder frequency response. This also means that the step response of the impedance in parallel should correspond to the high frequency response portion of the overall feeder frequency response. The construction of the pseudo-Norton's source is provided in section IV-A while the construction of the impedance in parallel is provided in section §IV-B.

A. *The Pseudo-Norton's Source*

The pseudo-Norton's source will consist of an inverter stage with its associated controls, a filter as well a transformer. Generally speaking, any inverter must contain a filter to shape the output waveforms by rejecting the high frequency switching harmonics. Inverter manufacturers can use transformerless [9] technology, but this is outside the scope of this paper. The validity of the current methodology is yet to be investigated under transformerless technology.

To construct the pseudo-Norton's source, the inverter MVA rating must be scaled up by a factor equal to the total number of inverters on the feeder. Many vendors supply proprietary EMT models of their inverters that has the number of inverters or the MVA variable. If the user is using a custom EMT model, then the model must have the MVA rating or the number of inverters variable. The controls of the inverter are to kept the same without any change. The values of the inductance and the capacitance of LC filter are also to be scaled up by the number of inverters. Lastly, the ISU transformer MVA rating is also to be scaled up by a factor equal to the number of inverters without changing the per unit impedance of the ISU transformer.

In this paper, we used a confidential model supplied by the manufacturer. The model has proprietary control algorithms, proprietary switching topology, LC filer and an ISU transformer. We only scaled the model as described in this section.

B. The Impedance in Parallel

It is necessary that the parallel impedance represents the high frequency response of the collector system. Since it is typical in power flow studies to represent the cable sections in the collector system using pi-models, the reader is to be warned against such representation in EMT type analysis as this representation is only valid at the power frequency. The parallel impedance is nothing other than a frequency dependent impedance that captures the high frequency response of the cable sections in collector feeder. Thus the cable sections along the feeder have to be modeled by a suitable frequency dependent model. The user has two choices:

1) Perform a frequency scan on the feeder with all inverters removed from the project (ISU transformers have to be open-circuited as well as the feeder breaker). Using that frequency scan, the user can use vector fitting [10], [11] to construct a frequency dependent model. Passivity has to be enforced upon the resulting fitting by insuring that negative resistance is not a result of the fitting. Negative resistance causes instability in the EMT simulations.
2) Keep the feeder intact without performing a vector fitting. This means that the cable sections are to be kept in the model but without the inverters, LC filters or the ISU transformers.

Theoretically, both methods should represent the same impedance. The first choice above can be done very quickly in PSCAD™/EMTDC. However, PSCAD™/EMTDC does not enforce passivity on the resulting frequency dependent model. Due to that, the authors used the second choice and they will treat the first method in a separate publication.

The authors also noted that for the equivalencing to produce satisfactory results, some cable sections in feeder have to be left out from this equivalencing process. It turned out that the first cable section has to be removed from this frequency dependent impedance. The overall reduced order model is shown in figure 6.

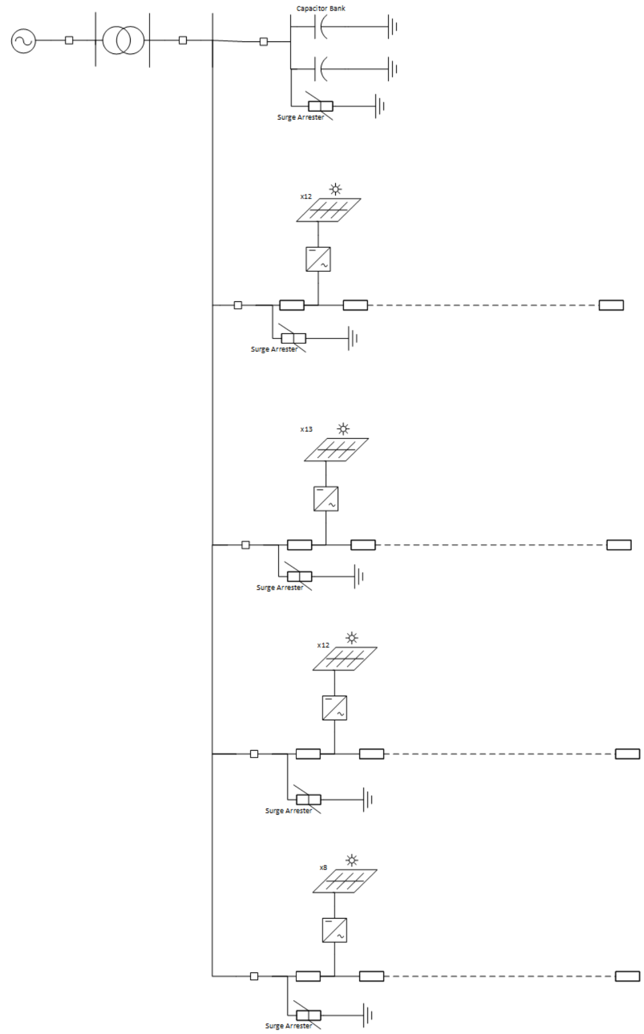

Fig. 6. Reduced Order Model

V. TOV Scenarios

A total of 52 cases (8 cases per feeder) have been used to benchmark the response of the reduced order model against the full order model. The cases are grouped into three main categories: feeder energization, load rejection and faults.

Since we are only interested in the SA evaluation, the voltage waveform has been monitored at the terminal of each SA. Current waveforms will be reported upon in a different publication. Circuit breakers are given close/open signal at around t=0.15 seconds.

The feeder energization cases are designed to test the validity of the construction of the parallel frequency dependent impedance. In these cases all inverters were offline and the feeder was initially de-energized. At certain time, the feeder breaker is closed and the response of both models are compared.

For the load rejection cases, the feeder was initially energized and then the circuit breaker was abruptly opened. Load rejection cases are the most important ones as evident from the tests supplied by the manufacturer in section §III. Load rejection cases should reveal whether scaling, grouping the inverters and placing them after the first cable section of each feeder is a valid approach.

Finally, fault cases have been performed. These are single line to ground , line-line and three phase to ground fault on the feeder. table I summarizes the cases that have been performed for each feeder.

VI. Results

Due to paper length requirement, only the key scenario results of the benchmark cases are discussed as part of this study. Specifically, scenarios B2, C1, C2, and D1 we will be discussed in further detail. The voltage at the MV bus is measured and compared. It should be noted that any switching operation happens around t=0.15 seconds. In all the figures below, the waveforms with dashed lines represent the reduced order model while waveforms with the continuous lines represent the full order model.

TABLE I
BENCHMARK CASES

Study Scenario	Case Number	Description
Case A: Project energization	A1	Energization of a feeder with capacitor banks ON
	A2	Energization of a feeder with capacitor banks OFF
	A3	Energization of all feeders with capacitor banks ON
	A4	Energization of all feeders with capacitor banks OFF
Case B: Capacitor switching	B1	Energization of both capacitor banks at 20% project output
	B2	Energization of both capacitor banks at 100% project output
	B3	De-energization of both capacitor banks with 20% project output
	B4	De-energization of both capacitor banks with 100% project output
Case C: De-energization/ load rejection	C1	Tripping of a feeder with capacitor banks OFF
	C2	Tripping of a feeder with capacitor banks ON
	C3	Tripping of whole project with capacitor banks OFF
	C4	Tripping of whole project with capacitor banks ON
Case D: Various faults	D1	LG fault on a feeder with capacitor banks ON
	D2	LG fault on a feeder with capacitor banks OFF
	D3	LL fault on a feeder with capacitor banks ON
	D4	LL fault on a feeder with capacitor banks OFF
	D5	LLLG fault on a feeder with capacitor banks ON
	D6	LLLG fault on a feeder with capacitor banks OFF
	D7	LG fault at 138 kV HV substation bus with capacitor banks ON
	D8	LG fault at 138 kV HV substation bus with capacitor banks OFF
	D9	LLLG fault at 138 kV HV substation bus with both capacitor banks ON
	D10	LLLG fault at 138 kV HV substation bus with both capacitor banks OFF

For Case A scenarios in table I, the response of the reduced order model is identical to the response of the full order model. This because in the reduced order model, the feeder has been left intact as mentioned in section §IV-B and energization occurs with the inverters offline, i.e., the inverter response is not part of the overall response and the voltage transients obtained and are due to the response of the feeders only.

For Case B scenarios, it is noted that the voltage waveforms of the reduced order model have more oscillations than the detailed EMT model. This is due to the fact that when the inverters are distributed across the feeder, cable sections of the feeder act as a filter that suppresses unwanted harmonics. However, in the reduced order model, only one cable section exists before the measuring point. Even though, we increased the inverter filter size, we do not get an exact replica of the voltage waveform of the detailed system model. The response of the reduced order model as well as the detailed model is shown in figure 7. However these higher harmonics don't affect the energy absorbed by the SAs since they are fast transients and much below the MCOV of the SAs.

For Case C scenarios and apart from the higher frequency harmonics, the response of reduced order model of one of the phases seems to not agree very well with the response of the full order model in Case C1. However, this disparity between the two responses causes a 15 kJ difference only between the calculated absorbed energy of the SAs between the detailed and reduced order model. Given that the energy handling capability of the SAs is 219 kJ, the error is less than 7%. The response of the reduced order model as well as the detailed model is shown in figure 8. For Case C2, the reduced order model follows the detailed model except for higher frequency harmonics as in Case B scenarios. Only Case C1 shows such disparity and other Case C scenarios exhibit the same type of response as in Case B scenarios.

For Case D scenarios, the observations from Case A scenarios still hold. The response of the reduced order model as well as the detailed model is shown in figure 10.

All cases in this section has been focused on the response of Feeder 1. However, all other feeders exhibit the same response as Feeder 1. In all scenarios, the run time of the full order model is 8 hours per scenario on a workstation having 6 cores at a clock speed of 3.2 GHz and 32 GB of RAM. For the reduced order model, the simulation run time does not exceed 6 minutes for any scenario.

VII. CONCLUSIONS

In this paper a systematic way of reducing the order of solar PV project at the substation level has been presented. The method is shown to capture the response of the collector

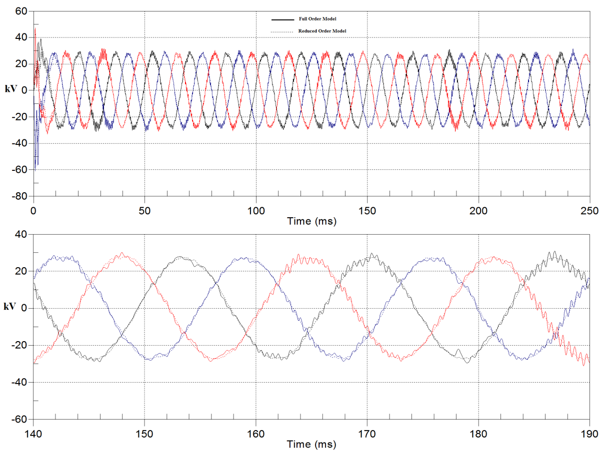

Fig. 7. 34.5 kV bus three phase voltages for Case B2 for feeder 1

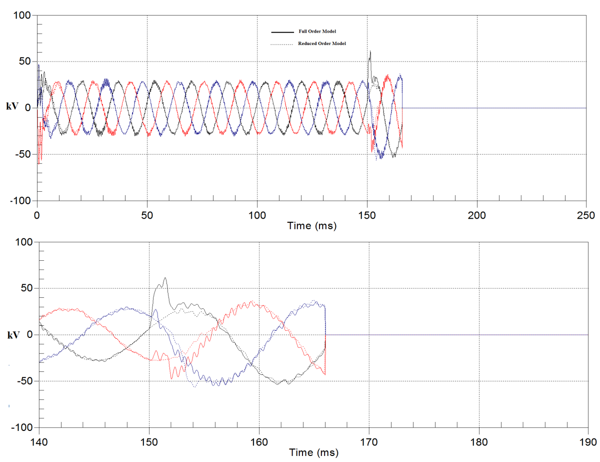

Fig. 8. 34.5 kV bus three phase voltages for Case C1 for feeder 1

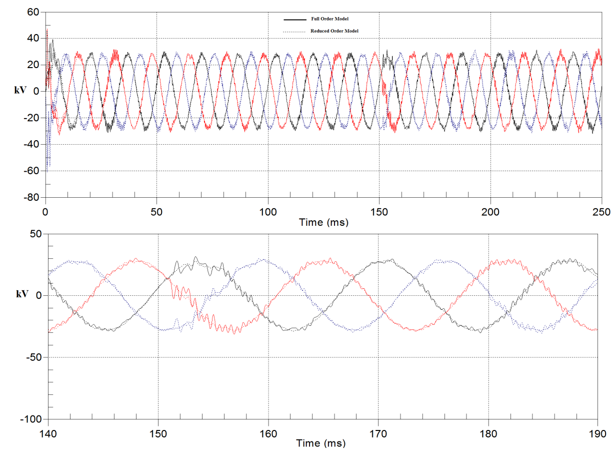

Fig. 9. 34.5 kV bus three phase voltages for Case C2 for feeder 1

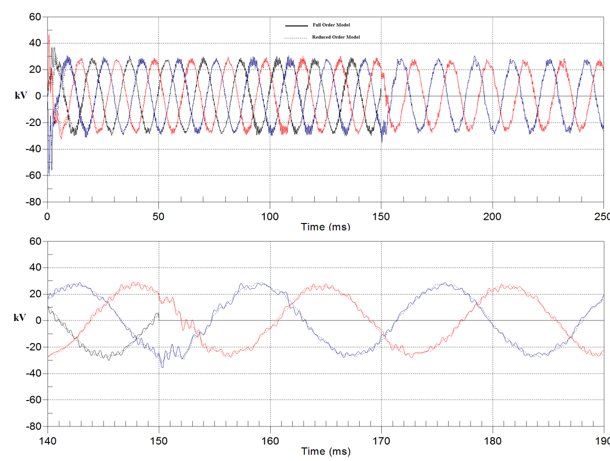

Fig. 10. 34.5 kV bus three phase voltages for Case D1 for feeder 1

system under various TOV scenarios to a satisfactory accuracy. The reduced order model takes much less time to run as compared to the full order model. This makes it useful in analyzing a large number of scenarios without the need for a highly capable computer.

The analysis in this paper is only limited to the SAs in the substation. If the feeder has SAs at the ends of the collector system- as usually the case- the method here will not be applicable but another method needs to be used to evaluate those SAs and will be analyzed in future research. Theoretically speaking the SAs in the substation are the ones that are under the most severe duty, and if those arresters can be shown to withstand various TOVs, then all other SAs in the project should be safe as well as long as they have the same capability.

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