Efficient EMT modeling approach to studying resonance phenomenon in PV and wind energy systems

M. Pielahn, K. Mudunkotuwa, A. Ranaweera, D. Muthumuni

***Abstract*- Current and voltage harmonics generated within renewable energy systems, such as PV plants and wind farms, may interact with the natural resonance points of the electrical network. Large EMT based simulation studies representing PV or wind farm collector systems, with large number modules, are computationally inefficient. In particular, this is a major concern when significant numbers of simulations have to be performed to study different operating scenarios as well as potential mitigation options. This paper presents an efficient approach to model collector systems of solar or wind farms. The method is developed with the particular case study of a 100 MW solar power plant, but is equally applicable to wind collector systems. With this procedure, renewable energy collector systems can be aggregated while preserving the frequency response characteristics, in turn making EMT simulations computationally efficient. The proposed method is verified through EMT simulations.**

***Keywords*: collector aggregation, EMT modeling, harmonic resonance.**

I. Introduction

Harmonic resonance issues in renewable energy systems, in particular wind farms, have been studied extensively in recent decades since the large-scale emergence of renewable energy sources and interconnection to large grid and distributed networks [1]-[10] (See [9] for a detailed overview of resonances in wind farms). Such systems contain both capacitive and inductive elements and therefore always have one or more natural resonance points, of either parallel or series resonance type, or both.

Modern renewable energy systems containing power electronic converters can produce a spectrum of harmonics over a wide frequency range. Further, other sources of harmonics may be present, such as harmonics generated during grid side disturbances. If a harmonic generated by the renewable energy generators is close to a naturally occurring resonance point of the system, there is a potential for sustained resonance. Such conditions must be identified at the design stage of a generation interconnection project to avoid undesirable situations such as equipment damage and power curtailment.

The system resonance points are characterized by the characteristics of network. These include lines, transformers and shunt devices. In renewable energy systems utilizing power electronic converts, it is common to include harmonic filters on the low voltage side of the step-up transformer. The filter characteristics can have a significant impact on the resonance points. Further, certain harmonics generated within the renewable energy system may either be avoided altogether by considering at the design phase, or by attenuating them with carefully designed filters [1], [2].

Collector systems of solar or wind farms may consist of a large number of machines, power electronic converters and cable sections. To simulate all elements in full detail is computationally inefficient, particularly when power system studies call for several simulations with different operating scenarios and potential mitigation options.

To overcome computationally time-consuming simulations, it is desirable to aggregate solar or wind energy systems into simpler, yet equivalent, systems. In terms of wind farms, work has been done in establishing procedures for aggregation [3], [11]. These methods typically derive equivalent line sections of the collector systems, and focus on accurate modeling of wind turbine generator types [4], [5].

In this paper, a systematic method is developed to aggregate collector networks, inspired by a particular case study of a 100 MW solar power plant. However, the procedure can be applied to most solar or wind energy systems. The method is unique in that it makes use of a curve-fitting procedure of the equivalent network impedance such that the frequency response around the resonance point is preserved.

The proposed method was successfully used to identify potential resonance problems at the 100 MW Alamo 5 solar power-plant to be built in Uvalde, Texas. Mitigations were recommended based on the studies that are to be implemented in the inverter design. This is validation of the proposed aggregating approach presented in this paper.

II. Solar Plant Overview

The Alamo 5 solar power plant has a maximum capacity of 100 MW and occupies 50 integrated sub units (ISUs) with each ISU rated at 2 MVA. The ISUs consist of a 2 MVA three winding transformer, two LC filters and two 1 MVA inverters.

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Fig. 1 shows the configuration of one ISU, with the inverters represented as voltage sources for simplicity in the diagram. In what follows, the inverters are modeled as voltage sources since the aggregation method is of interest.

The solar collector system is divided into four main branches as shown in Fig. 2. Each branch consists of a different arrangement both in terms of number of ISUs and connection of ISUs within each branch. The four branches are connected to a substation that further connects to a generator step-up (GSU) transformer. The GSU is then connected to the grid network.

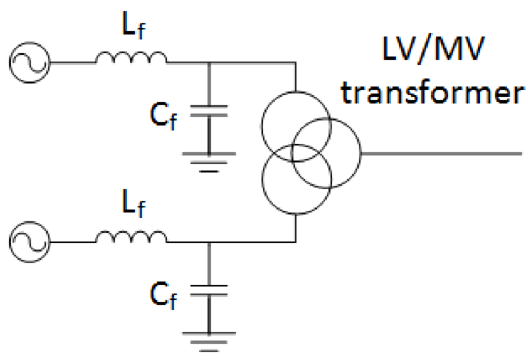

Fig. 1. ISU configuration.

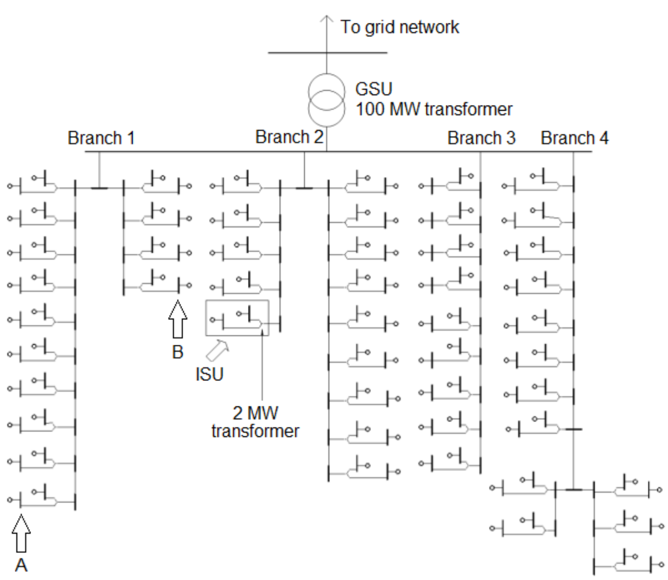

Fig. 2. Solar collector system consisting of 50 ISU and a GSU transformer.

III. Impedance Scanning

Plots of network impedances at different frequencies are very useful in identifying possible harmonic resonance conditions that can give rise to a number of problems including voltage distortion and stress on equipment insulation.

Depending on the location of the scan, vastly different impedance plots can be obtained. Scanning at different locations not only yields different results, but also gives detailed insight into the behavior of the system overall.

For example, Fig. 3 shows the frequency response (admittance plot) of the system when the scanning is from Point A on the first branch. For admittance plots, the valleys correspond to parallel resonance points while the peaks represent series resonance points [1], [2]. Around the 650-670 Hz range a series and a parallel resonance is observed in both curves. From preliminary studies, it was determined that it is this frequency range that is of interest. Other resonance points past 950 Hz are not of much importance in this case as the harmonics generated by the ISUs are more in the lower harmonic range.

Each ISU has capacitance and inductance and the various ISU modules can produce signature response plots that can identified.

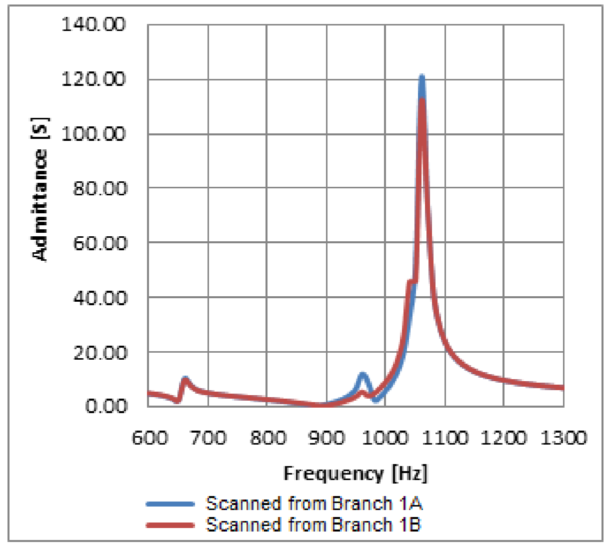

Fig. 3. Admittance scans at the two end points of branch 1.

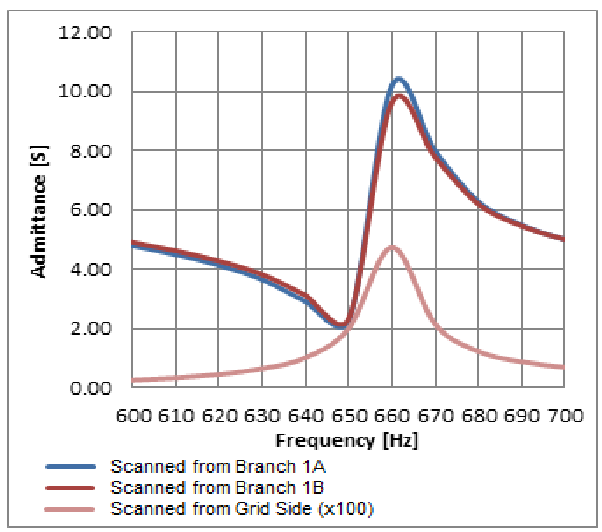

Fig. 4. Admittance scans at the two endpoints of branch 1 and at the grid side.

The result of scanning by looking into the collector system from the grid network is given in Fig. 4, with the portion of the above plots (in Fig. 3) superimposed. Here the *Grid Side* curve is scaled by a factor of 100 for demonstration purposes. Notice that the grid side scan does not have a parallel resonance point.

IV. TIME DOMAIN SIMULATIONS

In harmonic resonance studies for renewable energy collector systems, time domain simulations (on EMT platforms) are essential to identify the adverse interaction of inverter control design with the system that may create harmonic resonance issues. In these studies, use of detailed EMT models for inverter system gives reliable and accurate results.

Simulation of the entire solar farm with 100 detailed inverter modules is impossible on EMT platforms due to high computational demand. Therefore, the solar collector system has to be represented by means of an appropriate aggregate model without losing important frequency characteristics shown in Fig. 4.

V. INVERTER MODEL

For the purpose of aggregating the collector network, as outlined in the proceeding section, the inverters, without the LC filters, are modeled as simple voltage sources. The inverter LC filters were considered in the proposed aggregation procedure. After the aggregated network is developed, EMT simulations were performed with full detailed inverter models replacing the voltage sources and the LC filters.

VI. COLLECTOR SYSTEM AGGREGATE REPRESENTATION

The collector system has to be modeled accurately to capture the frequency profile of the system around an interested frequency range, which in this case is around the resonance point (660 Hz) that was identified during the impedance scan.

The system is modeled in PSCAD/EMTDC for this harmonic resonance study. In this study, the solar farm collector network cables are modeled as equivalent PI sections. The interconnection transformer and the transformers at each ISU unit are represented by the appropriate models.

The method of aggregation focuses on equivalencing each branch of the collector system. For example, as shown in Fig. 5, a branch consisting of four ISUs and line sections can be represented by one equivalent line section and four parallel ISUs. Afterwards the four parallel ISUs can be replaced by a single scaled ISU, assuming that they operate under identical input conditions.

As shown in Fig. 2, the collector system of this study consists of four branches. Therefore, it appears natural that the aggregated network is to be made from four sections, each corresponding to an aggregated branch of the collector system and aggregate inverter module.

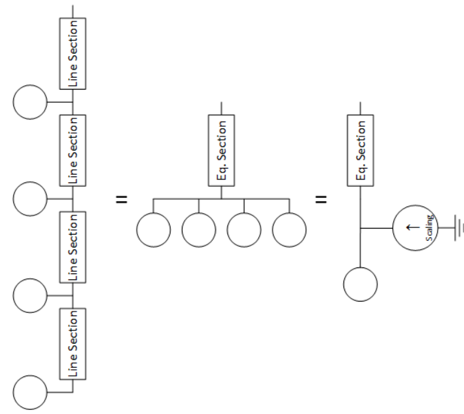

Fig. 5. Equivalencing a collector branch.

The aggregated branch represents the total cable segment. The final aggregated system has to preserve the same frequency response as the fully-detailed system. All inverters (voltage sources) in the branch become parallel and therefore current inject by each branch can be scaled to represent N number of units in all the branches. This enables an efficient way to simulate the entire solar farm by using only four inverter models, which is feasible in EMT simulations. With the fully aggregated system, EMT simulations can be carried out to investigate a wide range of harmonic resonance issues.

A. Weighted Averages

The cable data (R_{PI}, L_{PI}, C_{PI},) is normalized to one per unit length, as this makes the weighted average of each equivalent aggregated section simpler to determine. Thus the length of each section (d_i) is used as a free parameter for the aggregation calculations.

To demonstrate the procedure, the first branch (left most in Fig. 2) is used as an example and is shown in Fig. 6 with each section numbered for reference. The method is to calculate the equivalent PI section corresponding to the original 14 PI sections of this branch. The equivalent PI section is obtained by taking a weighted average of each of the resistance, inductance and capacitance. This method is similar to the aggregation method for a wind farm in [11].

For the particular example of branch 1, the equivalent resistance is calculated with the following equation:

$$R_{equiv} \frac{15R_0 + \sum_{i=1}^{10}(11-i)R_i + \sum_{j=11}^{14}(15-j)R_j}{N} \quad (1)$$

where N is the total number of section, in this case 15. The summation is broken into two separate sums because the branch is split after Section 0. Further, the indices on the summation are arranged such that the weight of each section corresponds to the number of sections attached further down the branch.

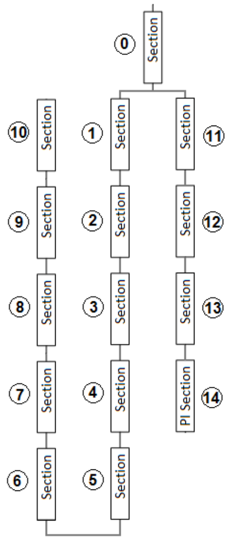

Fig. 6. The first branch of the collector system.

For example, cable section 1 (labeled with a 1 in Fig. 6) has a weighted factor of 10 as there are 10 sections attached below it including itself. Cable section 2 has a weight of 9, and so forth till the end of the chain. For that reason the zeroth section has a weight of 15 and is external to either of the summations.

Different branch arrangements will have different weighted averages and the corresponding formulae are determined from each branch schematic. Finally, the weighted averages for the impedance and the capacitance are done in a similar manner.

The unique aspect in our method is that the length of each line section (d_i) is left as a free parameter, which was normalized before. Fixing these length parameters is essential in ensuring that the frequency response characteristics of the aggregated collector impedance match to the original fully-detailed collector network.

B. Curve Fitting

Once the equivalent cable segment parameters are found, frequency profile of the equivalent segment should be plotted and compared with the frequency response of original fully-detailed system. If the resonance frequencies of the equivalent cable are off from original plot, the length parameters are adjusted until a close match is observed.

Looking from the grid side, Fig. 7. shows the original system admittance (black), and four aggregated system admittances (colors), each corresponding to different values of the free parameters. For simplicity, the free parameters were kept at the same length (all d_i = 0.5, 0.9, 1.5, 1.83), however this is not required. One could change each of the four parameters (representing each branch) independently from another in any way such that the desired frequency response is acquired.

Further, it can be seen in Fig. 7 that the valued d_i=1.83 correspond to a curve that closely resembles the actual system admittance. The fitted and the actual frequence response peak at approximately 659 Hz. The respective admittance amplitudes also fairly closely match, but may be improved by further fine-tuning the free parameters.

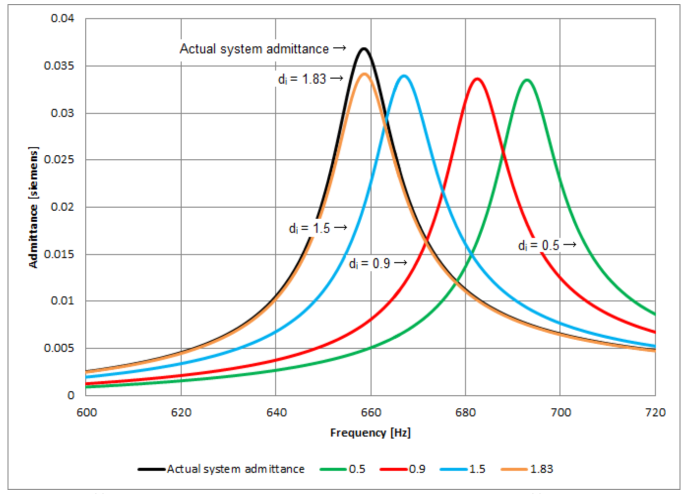

Fig. 7. Different length parameter values corresponding to different aggregated system frequency responses.

C. Power and current scaling

The final step is to replace the ISU units with a single corresponding ISU for each branch. The equivalent ISU is scaled to represent the total power of the individual ISUs. For example, the original first branch has 14 ISU units, each having a 2 MW output. Therefore, the equivalent aggregated branch must also have a 28 MW output with the appropriate current.

The scaling is done via a custom-made scaling module in PSCAD/EMTDC. This module preserves the waveform characteristics, including transients and steady-state operation, and scales the current and hence power accurately.

When the entire branch is aggregated it has a schematic as shown in

Fig. 8. The PV generator consisting of the aforementioned nine inverters is shown as a voltage source for simplicity. For the example of the first branch, the scaling value is 28.

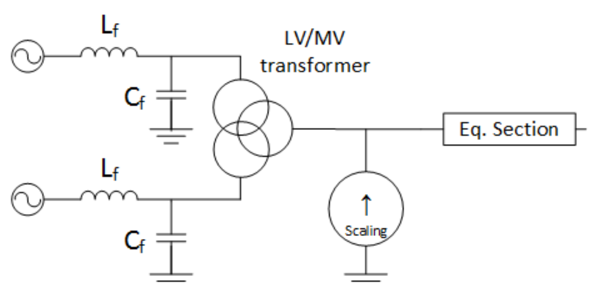

Fig. 8. Aggregated branch schematic.

VII. Simulation Results of Case Study

Two models were designed in order to test the aggregation method. The first is the detailed model as seen in Fig. 2. The inverters of the 50 ISUs were modeled as simple voltage sources. The second model is the aggregated system that consists of four aggregated branches.

Using these models PSCAD/EMTDC simulations were performed that computed the total harmonic distortion (THD) of the line voltage as measured on the low voltage side of the GSU transformer. The THD incorporated the first 255 harmonics that were calculated using the PSCAD Fast Fourier

Transform component. Both detailed and the aggregated models were injected with 1 V (RMS) harmonics of frequencies ranging from 650 to 670 Hz as seen in Fig. 9.

Since there are no other harmonics present (such as for example from switching of power electronic devices), the waveforms are perfectly sinusoidal. Therefore, without the injection of any harmonics, both models have a zero THD. Thus, the maximum THD value corresponds to the frequency of the resonance point. This suggests that the measure of the THD values, when injecting harmonics, can be used to find the frequency response and locate the resonance.

As can be seen in Fig. 9, the peaks of the detailed and aggregated models match very closely. Both peaks occur at a frequency of (659.5 ± 0.5) Hz. To get a fuller THD frequency response, results from a larger-spaced scan ranging from 100 to 1000 Hz is tabulated in Table 1. As expected, the THD is zero for both models if no harmonics are injected, which is shown in the first entry of the table.

Table 1 shows that for nearly all values, besides those in the vicinity of the resonance point as in Fig. 9, the THD values are close to zero. The THD values of the detailed model and the aggregated model are extremely similar, thus further implying that the aggregated system impedance closely matches to the detailed model.

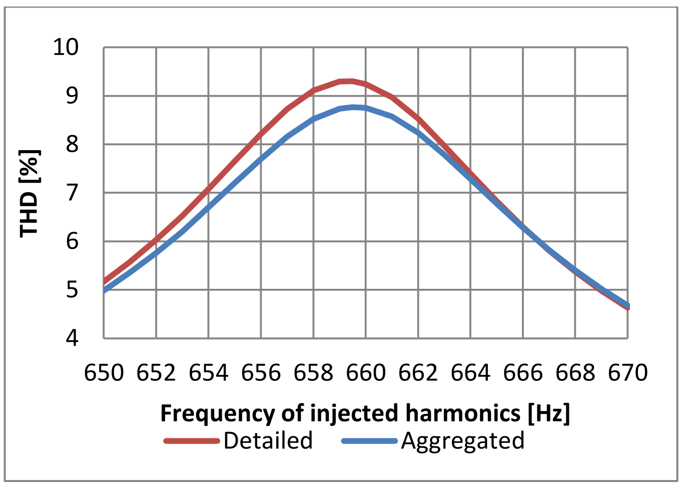

Fig. 9. Total harmonic distortion due to voltage harmonic injection of the detailed and aggregated models.

Table 1
THD values of detailed and aggregated models

Freq. of injected harmonics [Hz]	Detailed Model THD [%]	Aggregated Model THD [%]
0	0.00	0.00
100	0.148	0.148
200	0.177	0.177
300	0.207	0.207
400	0.263	0.262
500	0.397	0.396
600	0.996	0.996
700	1.386	1.370
800	0.387	0.383
900	0.218	0.216
1000	0.149	0.153

VIII. Conclusions

This paper presented a method to aggregate the collector systems of solar or wind farms in a manner that preserves the frequency response of the system impedance. It is important to capture the impedance characteristics accurately in order to perform EMT based simulations. The aggregation not only allows for more efficient simulations as large numbers of inverters and line sections are reduced to a manageable size, but also allow for investigations of resonance properties and resulting harmonic issues.

The frequency response of the aggregated system closely follows that of the original system. The simulation results of the fully-detailed system and the aggregated four-branch system compare very well. The THD values match up closely, with both peaking at a frequency of (659.5 ± 0.5) Hz. With more accurate fine-tuning of the free parameters, the amplitudes can be made to match even closer.

The method of aggregation established in this paper allows for detailed modeling of large renewable energy collector systems while maintaining an accurate system impedance response. Preserving the original impedance of the system is important for studies involving harmonic resonance issues.

This method was successfully used to identify potential resonance problems at a 100 MW solar power installation, during its design stage. Mitigations were recommended based on aggregate model studies that are to be implemented in the inverter design. This is validation of the proposed aggregating approach presented in this paper.

IX. References

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