

# Parameterization of Generic Positive Sequence Models to Represent Behavior of Inverter Based Resources in Low Short Circuit Scenarios\*

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## Abstract

The connection of large inverter based resources (IBR) in transmission systems is often located geographically and electrically far away from load centers. This, coupled with the displacement of synchronous machine plants, results in a reduction of the network short circuit strength at the point of connection. Under these conditions, state-of-the-art positive sequence simulation platforms and models can have difficulties maintaining numerical stability and/or providing an accurate representation of IBR plant dynamic behavior. As a result, computationally heavy time domain electromagnetic transient (EMT) simulations may be required to evaluate these systems. In this paper, a recently developed improved generic positive sequence model is parameterized to provide a representation of IBR behavior in low short circuit networks. Comparisons against generic and detailed EMT models demonstrate the suitability of the improved positive sequence model to study practical stability issues experienced with presently in-service plants. Such a model can provide some of the accuracy of an EMT representation with a much lower computational burden. The performance of the positive sequence model is validated against the behavior shown by both open white box and closed black box EMT domain models from around the world.

*Keywords:* Generic inverter model, numerical robustness, oscillations, weak grids

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## 1. Introduction

The increase in inverter based resources (IBRs) (or inverter based generation (IBG)) in transmission systems has brought to the forefront the need for accurate and validated

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mathematical models that represent the dynamic behavior of these power plants [1]. In a strong power system, such as one with a low equivalent Thévenin impedance, IBR controls can be programmed to operate with strict control of current injected into the network. Conventionally, IBR plants operate on a fixed power reference that is held constant in the transient time frame. To bring about such an operation, the control algorithm for current injection from IBR can be generally defined from first principles as shown in Fig. 1.

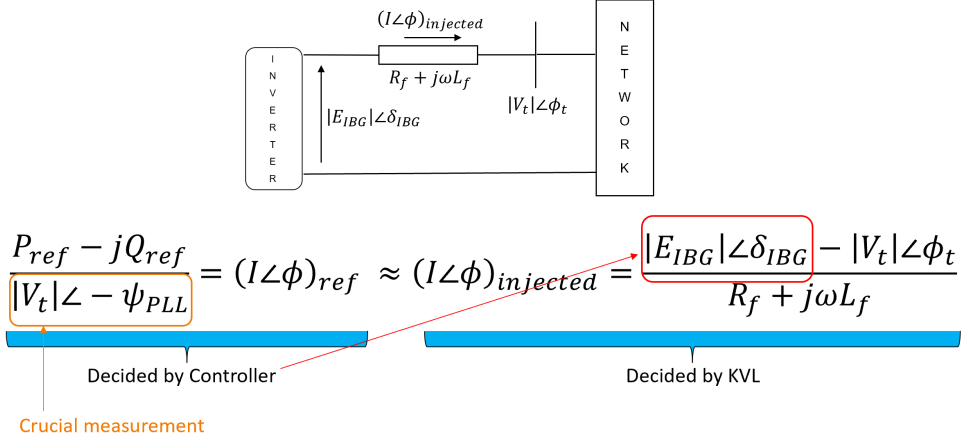


Figure 1: Mechanism of inverter operation defined from first principles based on Kirchhoff's laws

Here,  $|E_{IBG}| \angle \delta_{IBG}$  is the phasor representation of the sinusoidal voltage generated by the inverter (on its ac side),  $|V_t| \angle \phi_t$  is the phasor representation of the voltage at the point of synchronization, and  $R_f + j\omega L_f$  is the impedance between the inverter's ac side and the point of synchronization. The overall objective of the controls of an inverter is to ensure that  $(I \angle \phi)_{injected}$  (whose value is influenced by Ohm's and Kirchhoff's Laws and thus influenced by the grid) is almost equal to  $(I \angle \phi)_{ref}$ . The angle derived by the phase locked loop (PLL) is  $\psi_{PLL}$ . In order to meet this objective with a low time delay,  $|V_t| \angle \phi_t$  must not be overly sensitive to change in current injections, while  $\psi_{PLL} \approx \phi_t$  and  $|E_{IBG}| \angle \delta_{IBG}$  should be defined with minimal delay. If these requirements are met, an inverter can inject  $P_{ref}$  and  $Q_{ref}$  (often determined by a fixed power factor) successfully.

In a strong grid, such a control objective can be met with very low phase lag and time delay. However, as the proportion of IBRs increases in local areas of the existing system with low short circuit strength, there is a possibility of increased sensitivity of  $|V_t| \angle \phi_t$  to changes in both magnitude and phase of the injected current. The control structure of conventional IBR plants, if not appropriately tuned, can have difficulties maintaining stability in these circumstances [2]. This phenomenon appears both in simulation results and real networks with a high proportion of IBR. While there is a range of challenges that arises when connecting IBR in networks with low short circuit strength, this paper is focused on the interactions of IBR controls and high series network impedance.

As a reference, a 4 Hz oscillation event was captured in South Texas in 2011. When

the wind farm was weakly connected to the ERCOT system, poorly damped and undamped oscillations were observed for low and high dispatch levels respectively. Post event analysis demonstrated that wind plant controller needed to be tuned or the system strength increased in order to improve damping of the oscillations [3]. Similar events and observations have also been made in Australia [4].

Until relatively recently, use of positive sequence simulation platforms has been the standard practice for bulk power system planning studies around the world. Since IBR control algorithms are proprietary in nature, ‘black box’ or ‘user-defined’ simulation models are generally provided by the original equipment manufacturer (OEM) for studies in positive sequence. While these models do have the advantage of higher accuracy, there can be computational challenges, compatibility, and intellectual property difficulties associated with the use of many of these models when studying a large system [5]. While there are generic models developed for use in EMT tools [6], there is a need in industry for generic *positive sequence* models. To facilitate planning studies with large numbers of IBR, under the aegis of the Western Electricity Coordinating Council (WECC) Modeling and Validation Subcommittee (MVS), a suite of generic IBR models have been developed and improved over time [5]. These models are structured in a way (as shown in [5]) that enables them to represent the trend of the dynamic response of inverters from many different IBR vendors.

The present state-of-the-art generic positive sequence inverter model (named as REGCA in WECC nomenclature) represents an IBR as a current source without explicit representation of the dynamics of fast inner current control loops and phase locked loop (PLL)[5]. Until recently, as the system strength of many large power systems was considered to be sufficiently strong for IBR current injection these generic positive sequence models were suitable for use in planning studies. However, as the short circuit strength of the system reduces, not only do IBR plants have an increased probability of experiencing instability but, as described above, state-of-the-art positive sequence models may lose numerical stability and fidelity. As a result, a system planner is hindered in the use of positive sequence simulation tools to obtain a picture of the system dynamic behavior and may in-fact unknowingly base decisions on non-conservative, overly optimistic simulation results.

Presently, detailed EMT simulation studies which use black box models provided by IBR OEM are being performed in systems where low system strength issues have been observed either in simulation or in the field. However for large systems, running stability and contingency analysis on EMT simulation platforms can bring about a significant case preparation & computational burden [7]. The industry would benefit greatly from a model that can provide an improved indication of realistic IBR behavior in low short circuit conditions. A model which remains numerically stable in low short circuit conditions where the real plant can operate and then itself becomes unstable under the same conditions that the real plant becomes unstable would be such an improvement.

A generic positive sequence model has been previously developed specifically to represent IBR dynamic behavior under low short circuit conditions [8]. This paper

provides practical application examples and insight into the parameterization of this improved model. First, a comparison of the model’s positive sequence behavior to a generic white box EMT model is provided. The positive sequence model is then parameterized to represent the behavior of black box EMT models and comparison results are provided. It should be noted that the use of these advanced positive sequence models is not meant to replace EMT studies, but is rather meant to improve the accuracy of positive sequence studies relative to the existing state-of-the-art REGC\_A model.

Further, the use of these improved positive sequence models should be accompanied by detailed model validation exercises [9, 10, 11]. However, such an exercise requires participation from the OEMs as without their inputs, control parameters from a black box model (without block diagrams) can have little use. The objective of this paper is not to completely parameterize a generic model to replace an OEM provided black box model. However, the objective is to show that positive sequence domain platforms are indeed capable of capturing oscillations around 5 – 10 Hz that have been observed in systems around the world, provided the IBR model is structured and parameterized appropriately. One recommendation from this paper is to provide guidance to OEMs regarding methods in which positive sequence models could be constructed for low short circuit scenarios such that these oscillation modes could be captured. Examples show that the improved model exhibits voltage instability under the same network conditions as EMT models and that it remains numerically stable in low short circuit conditions where existing state-of-the-art models failed.

The rest of the paper is structured as follows: Section 2 provides a high level overview of the newly developed REGC\_C positive sequence generic model. Section 3 uses generic EMT models to showcase the ability of the REGC\_C positive sequence model to provide a representation of IBR behavior in low short circuit scenarios. Providing an example of black box EMT models, Section 4 shows potential parameterization options to use the REGC\_C model to represent behavior observed in the EMT domain. Concluding remarks are provided in Section 5.

## 2. The REGC\_C Model for low short circuit strength scenarios

Positive sequence simulations are based on a phasor simulation approach. At every time step of a transient simulation the angle of the grid voltage is directly obtained from the algebraic solution of the network. This approach thereby ignores the complete dynamic characteristics and any control interactions of the PLL. The recently developed REGC\_C generic model [8], under the suite of WECC generic models for IBR plants, includes a representation of the PLL dynamics while maintaining numerical stability.

To include these characteristics, the phase locked loop controller’s dynamics and the inverter’s inner current control loop dynamics are included in the positive sequence model as shown in Fig. 2. Here,  $V_{treal}$ ,  $V_{timag}$ ,  $I_{real}$  and  $I_{imag}$  are the real and imaginary components of the terminal voltage and injected current obtained from the algebraic solution of the network solution. The variables  $V_{td}$  and  $V_{tq}$  denote the  $dq$  axis components of the terminal voltage while the variables  $i_p$  and  $i_q$  denote the  $dq$  axis components of

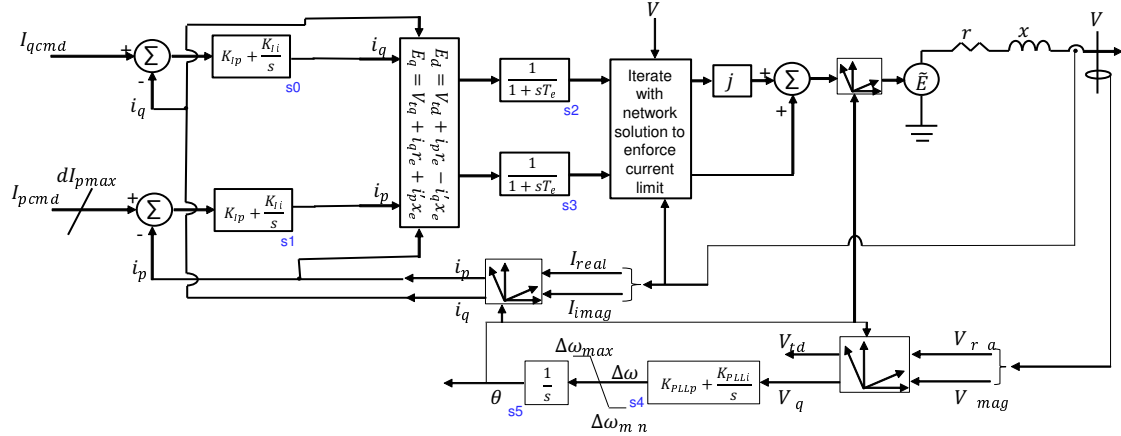


Figure 2: Complete block diagram of newly developed REGC\_C positive sequence converter model [8]

the terminal current. The PLL control gains are denoted by  $K_{PLLp}$  and  $K_{PLLl}$  while the inner current control loop gains are denoted by  $K_{ip}$  and  $K_{ii}$ . The inverter ac side filter is represented by its fundamental frequency representation  $r_e + jx_e$  while the inverter generated voltage is denoted by the  $dq$  axis components  $E_d$  and  $E_q$ . Current commands  $I_{pcmd}$  and  $I_{qcmd}$  are generated by outer loop controllers. While inclusion of these individual real and reactive components in each time step is standard practice in detailed EMT simulation models of power electronic converters, it has not been state-of-the-art for positive sequence simulation of the bulk power system. Their combined representation in the REGC\_C model serves to narrow the gap between the two simulation platforms without a drastic increase in computation time. Note that the objective of this paper is not propose this new REGC\_C model. The development of the model and its verification is available to the interested reader at [8]. Instead, the objective of this paper is to provide practical applications of use of this model, including an insight into parameterization of the model.

While increased numerical stability is brought about by the voltage source interface, a critical feature of this model is the current limiting block that sits in between the solution of the differential equations of the model and the algebraic equations of the network. Due to its voltage source interface representation, and the sequential solution approach used by positive sequence simulation platforms to solve differential algebraic equations, the current injection from the model during large system events (such as occurrence of a fault) can be greater than the current limit specified for the inverter. In order to maintain the current within its limits, at each time step, iterations between the value of injected current and the network voltage have to converge to obtain a converged network solution. Detailed explanation of the working of this block is provided in [8] and [12].

Since this model has representation of the dynamics of the inner current control loop and PLL, if appropriately parameterized, it can provide a representation of IBR behavior in low short circuit environments in a robust manner. Further, if oscillatory



by  $K_{ppll}$  and  $K_{ipll}$  while the inner current control loop gains are denoted by  $K_{pi}$  and  $K_{ii}$ . The inverter ac side filter is represented by its fundamental frequency representation  $jL_f$  while the inverter generated voltage is denoted by the  $dq$  axis components  $E_d$  and  $E_q$ . Current commands  $I_d^{ref}$  and  $I_q^{ref}$  are generally provided by outer loop controllers, but will be kept at fixed constant values in this section of study. These reference values of current are selected to represent an operating condition of 195 MW active power at a power factor of 0.98, which results in approximately 40 Mvar of reactive power. At this operating condition, the IBR is fully loaded at 200 MVA. In the EMT domain, the value of the control gains are:  $K_{pi} = 0.5$ ,  $K_{ii} = 20.0$ ,  $K_{ppll} = 60.0$ ,  $K_{ipll} = 700.0$ . The inputs and outputs of the current control loop are in per unit (pu) on the MVA base of the IBR. The input voltage to the PLL is in pu while the output frequency is in rad/s. The filter inductance  $L_f$  has a value of 0.15 pu. The dynamic behavior of the system equivalent is represented using a round rotor synchronous machine model with  $H = 9999.0s$  and  $X_d'' = 0.1217pu$ . The current rating of the machine is varied to represent different system strength conditions. Additionally, a simple static excitation system model (SCRX) is also used to maintain voltage at the terminals of the machine. The entire simulation is run at a  $5\mu s$  time step.

In the positive sequence domain, the IBR is represented using only the REGC\_C model. As can be seen from Fig. 2, the model accepts current reference commands and processes them through an inner current control loop and PLL before generating an output voltage. However, the value of control gains used in the positive sequence domain differ from those used in the EMT domain. In order to represent similar performance, the current control loop gains in the REGC\_C model were kept as 0.5 and 20.0, while the PLL gains were set to 20.0 and 400.0 respectively for the proportional and integral (PI) components. All other parameters such as filter inductance, MVA rating, and pu representation are the same between positive sequence and EMT models.

With this setup, the dynamic behavior of the system for both short circuit ratios (SCR) of 5.0 to 3.0 are shown in Fig. 5. SCR is defined as the ratio between the short circuit MVA capacity at the point of interconnection with the rating of the device. For example, if short circuit MVA capacity at the bus is 300 MVA and the rating of the IBR device is 100, then SCR is  $300/100 = 3.0$ . The value of the SCR is modified by modifying the rating of the synchronous machine source at bus 3. Because positive sequence simulations are initialized from a steady-state power flow solution, a small signal disturbance is applied at bus 2 in the form of a high impedance fault. It can be observed from the figure that even at SCR = 5.0, there is poor damping in the network and when SCR changes to 3.0, the system exhibits sustained oscillations. Here, both the EMT model behavior and the behavior of the positive sequence REGC\_C model are comparable in terms of trend of response. In contrast, the behavior of the present state-of-the-art REGC\_A model shows a stable response. The REGC\_A model was parameterized consistent with industry recommendations.

At this point it may be helpful to provide an explanation for the reduced value of control gains in the positive sequence REGC\_C model as compared to the values in the EMT model. Consider a simple integral controller with an ideal unity plant as shown

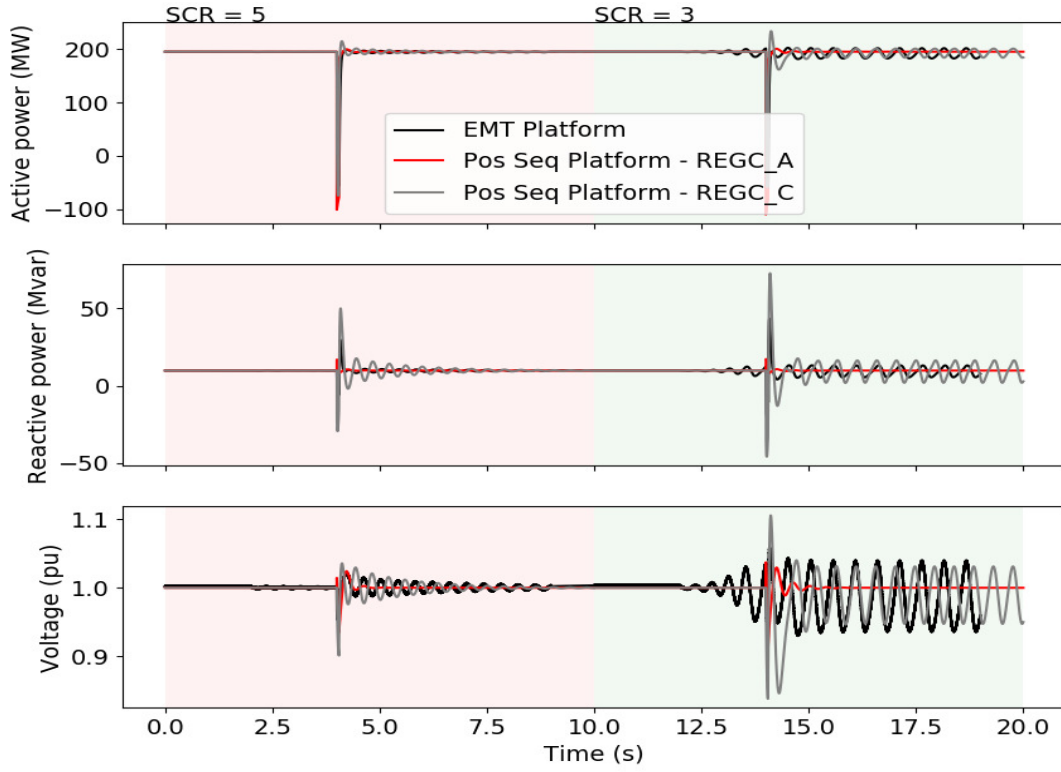


Figure 5: With reduction in SCR, comparison of dynamic response between EMT model and positive sequence generic models of IBR operating with constant current reference values

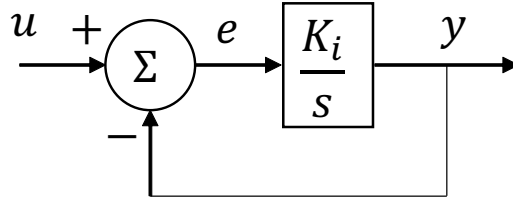


Figure 6: Simple integral controller with ideal unity plant

in Fig. 6. While carrying out numerical integration (as is done in all power system simulation software), the value of output  $y$  at time step  $t$  with an integration time step of  $\Delta t$  can be obtained as,

$$\begin{aligned} y_t &= y_{t-1} + K_i (u - y_{t-1}) \Delta t \\ \Rightarrow y_t &= y_{t-1} (1 - K_i \Delta t) + K_i u \Delta t. \end{aligned} \quad (1)$$

The value of output  $y$  at time step  $t - 1$  can be obtained as,

$$y_{t-1} = y_{t-2} (1 - K_i \Delta t) + K_i u \Delta t. \quad (2)$$

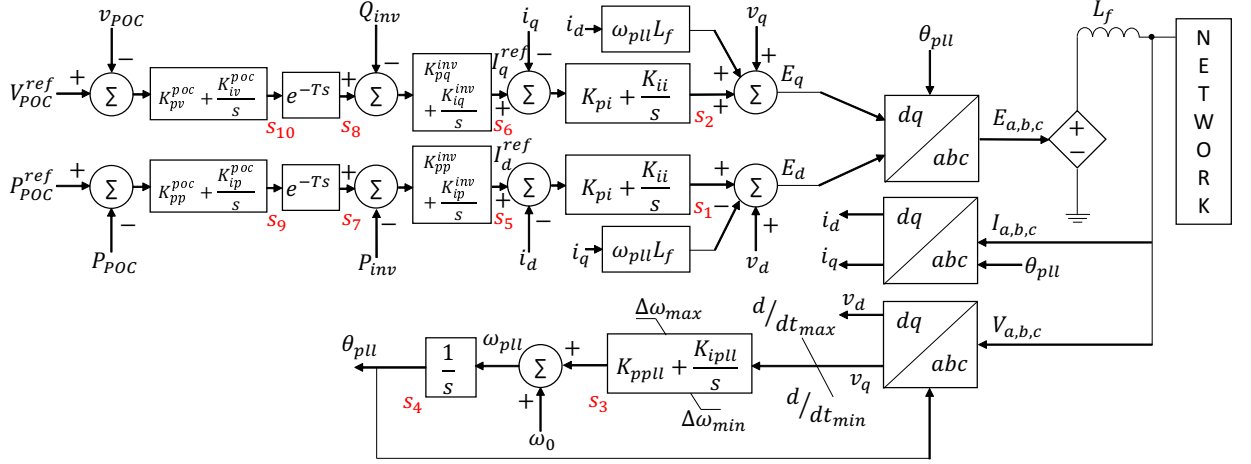


Figure 7: Layout of control topology for PV plant operating with point of connection P and V control

Substituting from (2) into (1) results in,

$$y_t = y_{t-2} (1 - K_i \Delta t)^2 + K_i u \Delta t (1 + (1 - K_i \Delta t)). \quad (3)$$

If we now track back in time, using the expression for sum of terms of a geometric progression, we can obtain the value of output  $y$  at time step  $t$  from any starting time instant  $n$  written as,

$$y_t = y_{t-n} (1 - K_i \Delta t)^n + u (1 - (1 - K_i \Delta t)^n). \quad (4)$$

Consider a step change in input  $u$  is applied, and if we consider  $y_{t-n} = 0$  to be the value of output  $y$  just before the application of the step, then (4) simplifies into  $y_t = u (1 - (1 - K_i \Delta t)^n)$  with  $u = 1$ . As the aim of the integral controller is to reduce error to zero while bringing output  $y_t$  to a value of 1.0, as the numerical integration progresses  $(1 - K_i \Delta t)^n$  should tend towards a value of 0.0. Here,  $n$  is the number of time steps needed by the integral controller to achieve this target. Since an absolute value of 0.0 is not practical in numerical computing domain (due to precision and round off error), we can assume that the target is achieved if,

$$(1 - K_i \Delta t)^n = 0.002. \quad (5)$$

Solving for  $n$  from the above equation, and subsequently solving for the time to reach steady state error using an integral gain of  $K_i = 700$  as an example, then in the continuous domain setting time ( $t_s$ ) can be evaluated as,

$$t_s = \frac{\ln(0.002) * dt}{\ln(1 - 700 * dt)} \approx 8.865ms. \quad (6)$$

However, when using the REGC\_C model in positive sequence simulations, it is recommended to use a numerical integration time step of  $1ms$  due to the representation of the inner current control loop and PLL. As a result, in order to achieve the same settling time of  $8.865$  ms, the integral gain can be evaluated as,

$$K_i = \frac{1 - \exp(\ln(0.002) \frac{1*10^{-3}}{8.865*10^{-3}})}{1 * 10^{-3}} \approx 500. \quad (7)$$

The simulation time step in positive sequence domain is a factor of 20 to 200 times larger than a typical EMT time step. This difference in the time step is large enough that even with an identical control structure differences in performance would be noticeable. Changing the values of the control parameters between the EMT and the positive sequence implementations is therefore unavoidable. This thus provides a conceptual background for the lower value of gains used in the generic positive sequence model REGC\_C. However, the derivation above was carried out with a single integral controller and an ideal plant with gain of 1.0 and zero phase angle. When the complete control topology is considered along with the electrical network, the mapping of controller parameters across the two software domains can be significantly more involved. Further, the dynamics of the electrical network are represented differently across the two software domains. Thus, while the same concept holds and it is reflected in Fig. 5, derivation of an exact analytical mapping of all the controller parameter values between the two simulation domains is future work.

### 3.2. PV plant with point of connection P and V control

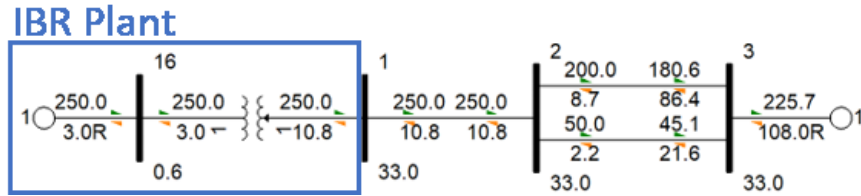


Figure 8: Single line diagram of PV plant with point of connection control connected to an equivalent source

With the previous section considering only the representation of inner current control loop and PLL, here, the control topology is extended to include outer loop active and reactive power controllers. Consider a PV plant connected at bus 1 (point of connection, POC) in Fig. 8 to an equivalent source at bus 3 through parallel lines with different values of impedance. The PV plant is assumed to have 110 individual 2.5 MW inverters with an overall controller topology as shown in Fig. 7[13]. A plant controller aims to maintain a fixed value of active power injection ( $P_{POC}$  with reference  $P_{POC}^{ref}$ ) at bus 1 while also controlling the voltage at bus 1 ( $v_{POC}$  with reference  $V_{POC}^{ref}$ ). To meet this objective, the plant controller issues active and reactive power reference commands which are transmitted to the inverter through a time delay of  $T = 0.1s$  to

represent the update frequency and communication delay of the plant level controller hardware. The controller gains for plant level active power and voltage control are  $(K_{pp}^{poc}, K_{ip}^{poc})$  and  $(K_{pv}^{poc}, K_{iv}^{poc})$  respectively. At the inverter level (bus 16), current reference commands are generated to satisfy the active and reactive commands from the plant controller. The controller gains for inverter level active power and reactive power control are  $(K_{pp}^{inv}, K_{ip}^{inv})$  and  $(K_{pq}^{inv}, K_{iq}^{inv})$  respectively. Two different sets of controller gains were evaluated, one with the time delay between plant controller and inverter represented as a dead time delay as in Fig. 7 and the other with the time delay between the plant controller and inverter represented as a first order transfer function  $\frac{1}{1+T_s}$ . The value of controller gains in the EMT domain common to both evaluated sets are  $K_{pp}^{poc} = 0.1, K_{ip}^{poc} = 1.0, K_{pv}^{poc} = 1.0, K_{iv}^{poc} = 10.0, K_{pq}^{inv} = 1.0, K_{iq}^{inv} = 100.0, K_{pi} = 0.2, K_{ii} = 20.0$ .

The values that are different between both sets are:

- Set 1:  $K_{pp}^{inv} = 0.25, K_{ip}^{inv} = 10.0, K_{ppl} = 50.0, K_{ipl} = 2000.0$  (dead time delay model as in Fig. 7).
- Set 2:  $K_{pp}^{inv} = 0.5, K_{ip}^{inv} = 13.0, K_{ppl} = 2.5, K_{ipl} = 1000.0$  (a first order transfer function  $\frac{1}{1+T_s}$ ).

The structure and pu value of filter inductance remains the same as in the previous section. Here the equivalent source is represented as an ideal voltage source. The simulations were run in EMT domain with a  $50\mu s$  time step. A reduction in SCR from 2.5 to 2.0 is brought about by tripping the higher impedance line between buses 2 and 3.

In the positive sequence domain, the REGC\_C generic model is parameterized with the same current controller gains of 0.2 and 20.0 respectively for the PI components. For set 1, the PLL PI gains were set to 44 and 2000 and for set 2, they were 4.5 and 500.0 for the PI components. Since the model in the EMT domain also has a representation of the outer loop controllers, the REEC\_A and REPC\_A generic models were also used in the positive sequence domain. In the plant controller REPC\_A model, the voltage and active power controller gains were kept the same as in the EMT model. Further, the time delay of 0.1s in the reactive power path was represented as a first order Padé approximation of  $\frac{1-0.05s}{1+0.05s}$  and represented as  $\frac{1}{1+0.05s}$  in the active power path for Set 1. For Set 2,  $\frac{1}{1+0.1s}$  was used in both reactive and active power paths. The REEC\_A model does not have explicit representation of a PI controller loop for inverter level active and reactive power control. Although it has a coordinated reactive power-voltage control loop, it was determined that this path would not be appropriate. As a result, the REEC\_A model is configured to generate current reference commands as  $I_d^{ref} = P_{ref}/|V|$  and  $I_q^{ref} = Q_{ref}/|V|$ . It is again observed that most of the controller gain values are the same across both the EMT and positive sequence domains. The equivalent source is represented by a classical generator model with  $H = 9999.0s$ .

The dynamic response of the network for a reduction and subsequent increase in SCR is shown in Figs. 9 and 11. It is observed that although not a perfect match,

a useful agreement in the general behavior of the response is obtained by using the REGC\_C generic positive sequence generic model while the present state-of-the-art REGC\_A model is unable to capture the response. Further, as shown in Fig. 10 a good match of the trend of response is also obtained when a three phase solid to ground fault is applied at bus 2 followed by lowering of the SCR from 2.5 to 2.0 along with clearance of the fault. These examples demonstrate that the new developed REGC\_C generic

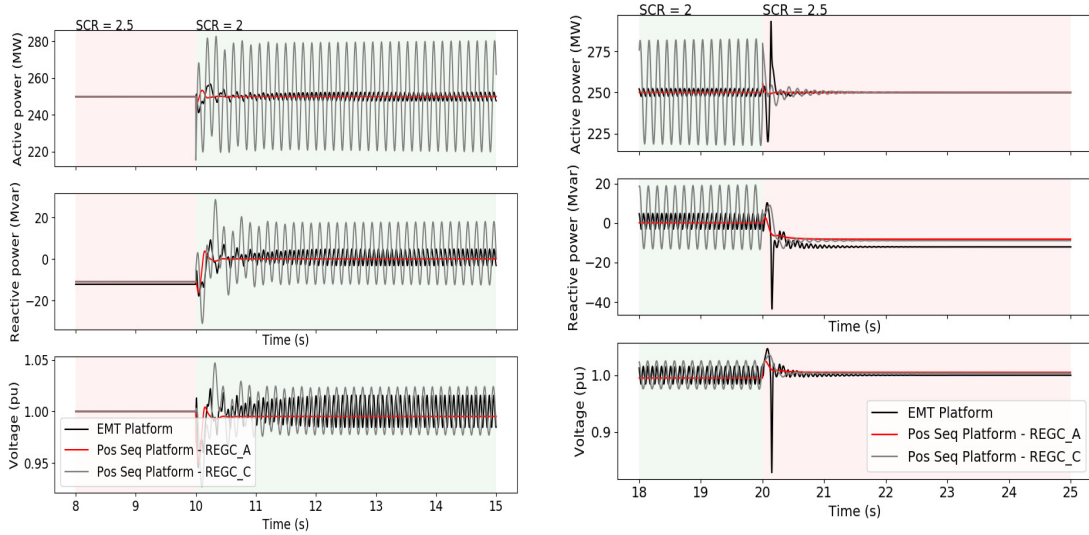


Figure 9: With parameter set 1, comparison of dynamic response between EMT model and positive sequence generic models of PV plant for SCR reduction (left) and SCR increase (right)

positive sequence model can provide useful results under low short circuit conditions that in general agreement with EMT domain simulations. This ability may be of benefit to system planners and industry in general by improving the accuracy and reliability of positive sequence domain system planning and operation analyses performed in low short circuit conditions.

#### 4. Performance validation against black box EMT model

In the previous section, the generic positive sequence REGC\_C model was parameterized using full knowledge of the EMT model, which in turn was generic in nature. However in practice, due to the proprietary nature of the IBR control algorithms, EMT models are generally black boxed. In such a scenario, the control structure that is employed is unknown to the user. As a result, there could potentially be significant differences between the control structure used in the REGC\_C model and the control structure used in the black box model. However, values of control gains from the black box model need not translate in the same manner to the corresponding control gains in the REGC\_C model. It is recommended that the OEM and plant developer always parameterize the generic positive sequence models such as the REGC\_C, REGC\_A, and

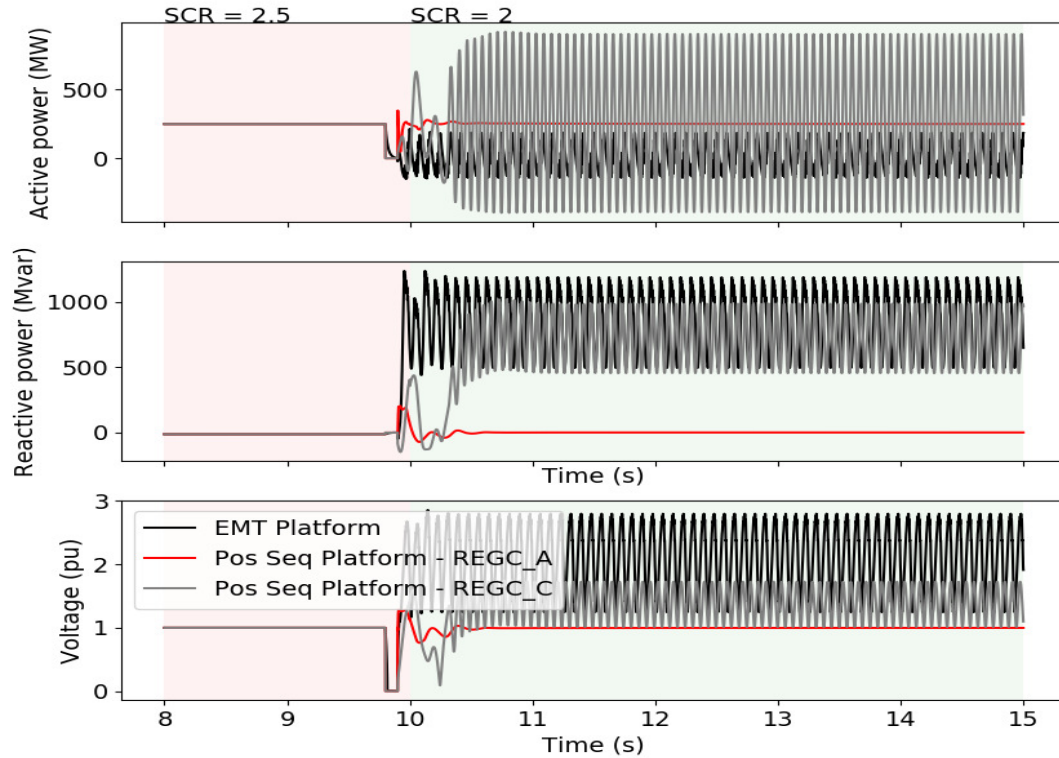


Figure 10: With parameter set 1, comparison of dynamic response between EMT model and positive sequence generic models of PV plant for three phase fault and reduction in SCR

the suite of REEC\_\* and REPC\_\* models. In the absence of this OEM parameterized model, while it is possible to parameterize the REGC\_C model based on simulation results, it must be kept in mind that such a parameterization must be validated by the OEM and plant developer for accuracy.

Three examples of parameterizing the REGC\_C model and comparison of the dynamic model behavior against EMT simulations using black box models of actual IBR plants from around the world are described in the subsections below.

#### 4.1. Solar plant in the Texas Panhandle

While conducting model validation tests of a solar plant using an EMT black box model under varying SCR values [14, 15], high frequency oscillations ( $\approx 55$  Hz) were observed under low SCR conditions. The equivalent system representation used to carry out these tests is similar to Fig. 3. In this case, the OEM provided a parameterized set of generic models represented by the REGC\_A + REEC\_B + REPC\_A models. The high frequency oscillations from the EMT model can be seen in Fig. 12. Additionally, even with the present state-of-the-art generic REGC\_A model, oscillatory behavior can be observed with the reduction in SCR. However, these oscillations are low frequency and  $\approx 7$  Hz.

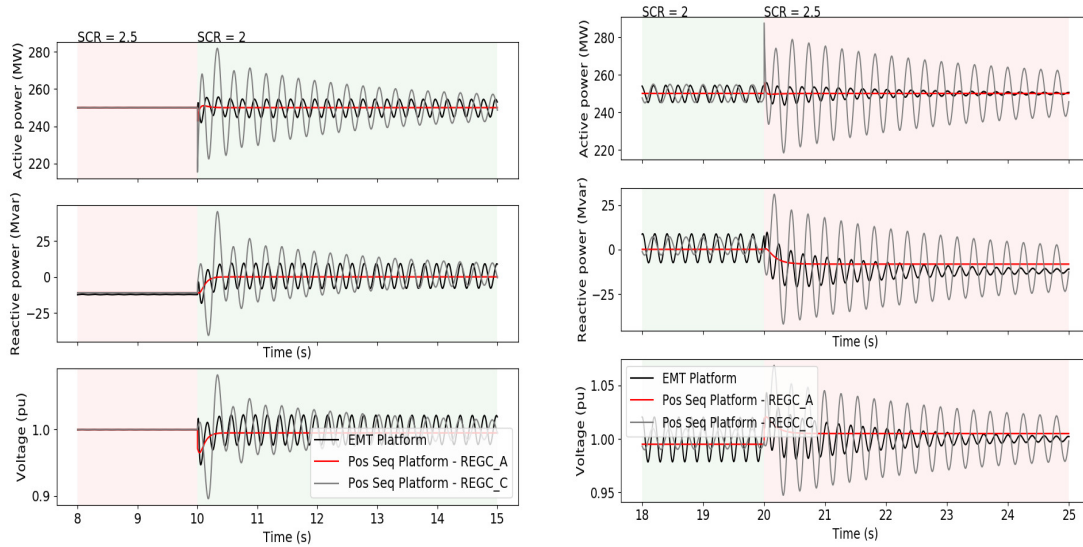


Figure 11: With parameter set 2, comparison of dynamic response between EMT model and positive sequence generic models of PV plant for SCR reduction (left) and SCR increase (right)

Since no further information regarding the control structure is available from the black box model, the REGC\_C generic model is parameterized with current controller gains of 0.05 and 700.0, while the PLL gains were set to 20.0 and 7000.0 respectively for the PI components. The parameterization of REEC\_B + REPC\_B models were unchanged. With this parameterization, the response obtained from the REGC\_C model is as shown in Fig. 12.

A commentary on the results is warranted. From a system planner’s perspective, it is possible that in this example use of the REGC\_A model is sufficient as the reduction in damping with reduction in SCR is visible. With use of the REGC\_C model, although there is a dominant mode of  $\approx 7$  Hz, there is also a superimposed mode of  $\approx 65$  Hz. The magnitude of this superimposed mode is however low. As there is no visibility into the black box model, it is not possible to comment on the appropriateness of the values of REGC\_C control gains. However, an increased accuracy of the oscillation frequency is observable. The figure successfully shows that the REGC\_C model can be parameterized with no OEM involvement and still successfully indicate at which point instability will occur.

#### 4.2. IBR plant in Australia

Detailed EMT studies carried out on a large scale system model with black box IBR models have shown the presence of 7 - 10 Hz oscillations from a IBR plant following a fault and subsequent line outage [4]. The IBR plant has a plant controller with droop based voltage control. Additionally, there are two static var compensators (SVC) in operation in the vicinity.

To study the system in the positive sequence domain, the IBR plant is represented

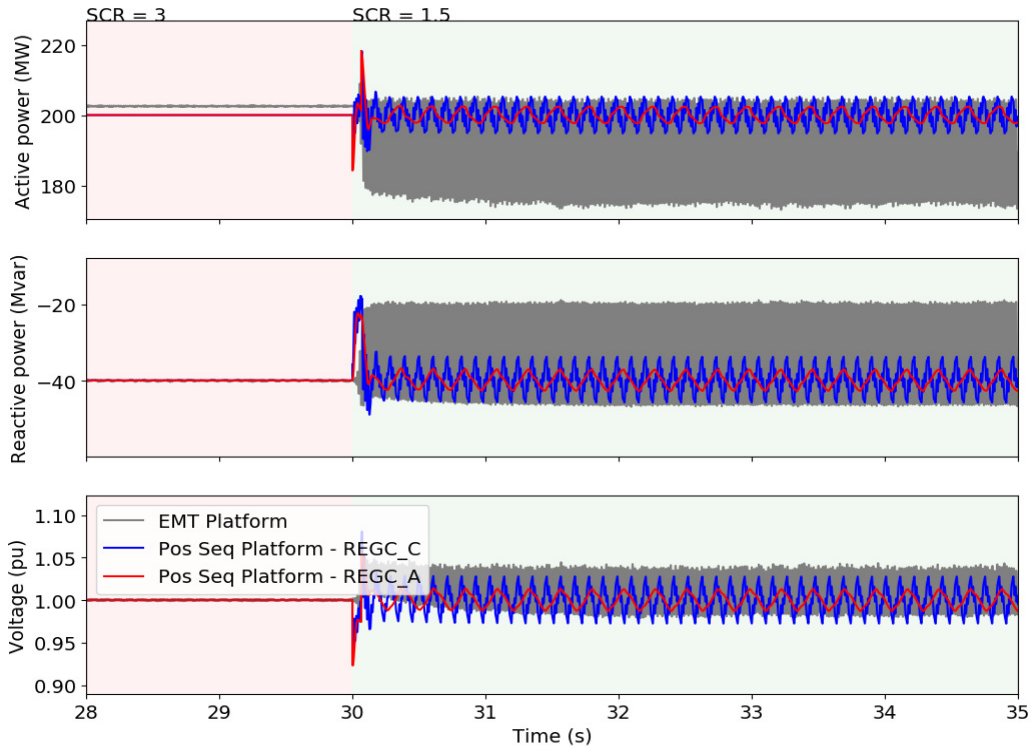


Figure 12: With reduction in SCR, comparison of response between black box EMT model and positive sequence generic models of solar plant in Texas panhandle

using the REGC\_C + REEC\_A + REPC\_B generic models. The SVCs are represented using user defined models. The REGC\_C generic model is parameterized with current controller gains of 0.25 and 20.0, while the PLL gains were set to 20.0 and 1600.0 respectively for the PI components. For the fault and line outage, the response from both simulation domains is shown in Fig. 13. Here again a commentary on the results is justified. The pre-disturbance difference in the reactive power output between both software domains is due to the fact that positive sequence models initialize from a power flow solution while EMT simulations achieve steady state after an extended time domain simulation. Here, while modeling network quantities, in EMT domain saturation and other non-linearities related to reactive power are modeled while these non-linearities are not modeled in a positive sequence power flow solution. As a result, there is a slight mismatch in the reactive power output. However, this mismatch does not have a significant impact on the observed oscillations. In the EMT domain simulations, the IBR plant and the SVCs were all represented using black box models. In the positive sequence domain, although the various OEMs (including the IBR plant) provided user defined models, the lowest SCR value for which their positive sequence models were mentioned to be accurate was higher than the SCR value at the device terminals after

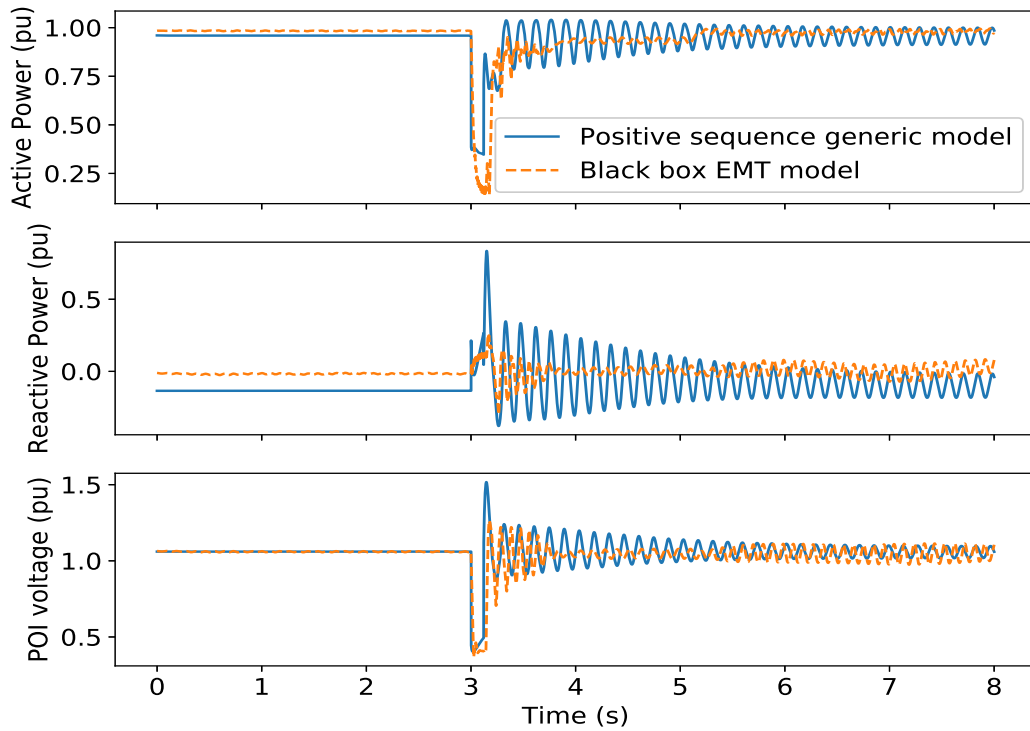


Figure 13: For a fault and subsequent line outage, comparison of response between black box EMT model and REGC\_C generic positive sequence model of IBR plant in Australia

the outage of the line. As a result, for this outage, the dynamic behavior from the OEM provided positive sequence user defined model of the IBR plant is unable to represent the observed oscillatory response. However, with parameterization of the REGC\_C generic model, a system planner can obtain an indication of instability.

#### 4.3. Solar plant in South Texas

While performing model validation and short circuit strength tests on a 200 MW solar plant using black box EMT models, it was observed that the plant's response to a large reduction in SCR was unstable when operated at an active power level greater than 0.7 pu (on the plant MVA base). The test system setup was similar to the set up shown previously in Fig. 8 wherein reduction of SCR is brought about by opening one of the two lines connected to the equivalent source. However, when a parameterized state-of-the-art REGC\_A generic model along with associated parameterized REEC\_A and REPC\_A models were used to replicate the behavior in the positive sequence domain, the REGC\_A model was unable to maintain numerical stability (indicated by repeated non-convergence messages) upon reduction of the SCR, even when operating at an active power level of 0.7 pu. While this in itself might be sufficient to indicate to a

system planner a need for more detailed simulation studies, it doesn't provide any useful information about the real plant's expected response to changes in SCR.

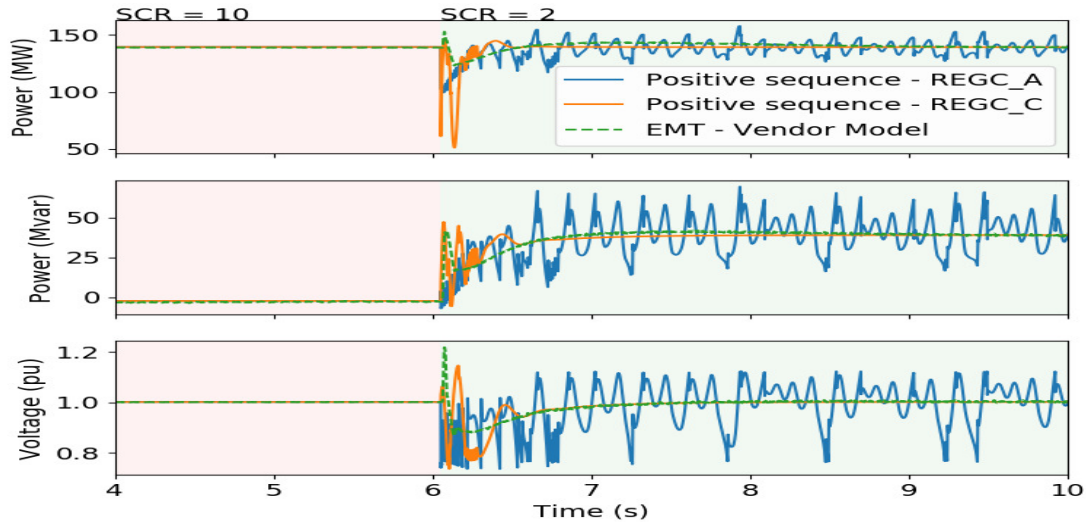


Figure 14: With reduction in SCR and with pre-disturbance operation at 0.7pu, comparison of response between black box EMT model and positive sequence generic models of solar plant in South Texas

To investigate the possibility of using the REGC\_C generic model in the same setup, it is parameterized with current controller gains of 2.0 and 30.0, while the PLL gains were set to 60.0 and 700.0 respectively for the PI components. With this parameterization, the response of the system is shown in Fig. 14 for pre-disturbance active power operating point of 0.7 pu. It can be seen that the EMT model response is stable while the REGC\_A model's response suffers from numerical instability. However, the response from the REGC\_C model is stable and tracks the transition to steady-state shown by the EMT model.

The response from the REGC\_C model at the initial occurrence of the disturbance is noteworthy and should be discussed. This response is not due to numerical non-convergence but rather due to the sequential solution approach of differential algebraic equations in positive sequence simulation platforms [12]. Further, upon increasing the pre-disturbance output of the solar plant to 0.8 pu, the response from both the EMT and positive sequence domains is shown in Fig. 15. Here it can be seen that the EMT model undergoes control cycling when the SCR reduces. The REGC\_C positive sequence model also starts to show control cycling but it is still able to hold onto a stable steady state trajectory. Further increasing the pre-disturbance operating point to 0.9 pu in the positive sequence model in Fig. 16 shows the sustained presence of control cycling and more importantly with stable numerical convergence.

In all three comparisons with black box EMT models, there is a degree of uncertainty associated with the parameterization of the REGC\_C model as there is no visibility

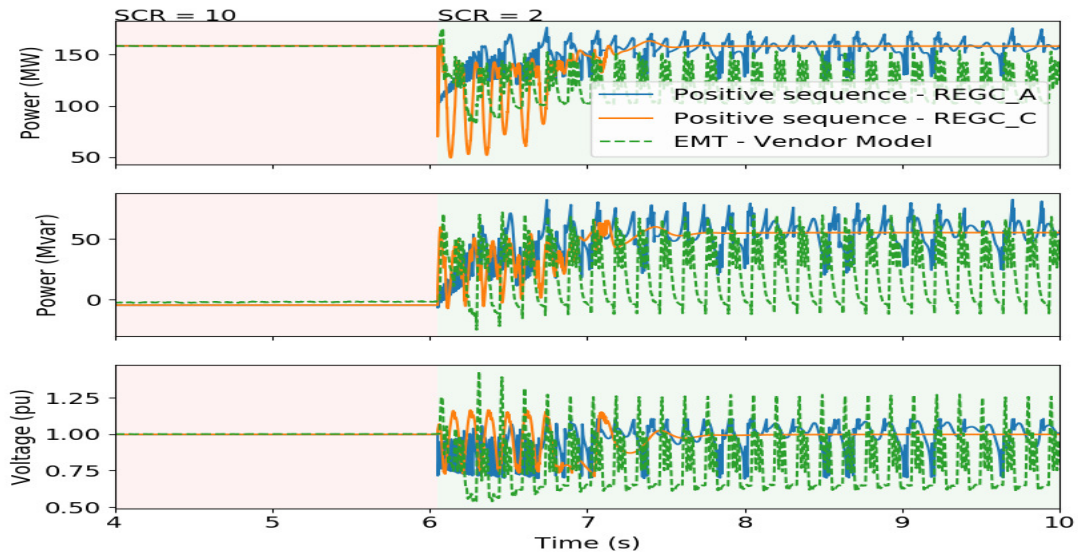


Figure 15: With reduction in SCR and with pre-disturbance operation at 0.8pu, comparison of response between black box EMT model and positive sequence generic models of solar plant in South Texas

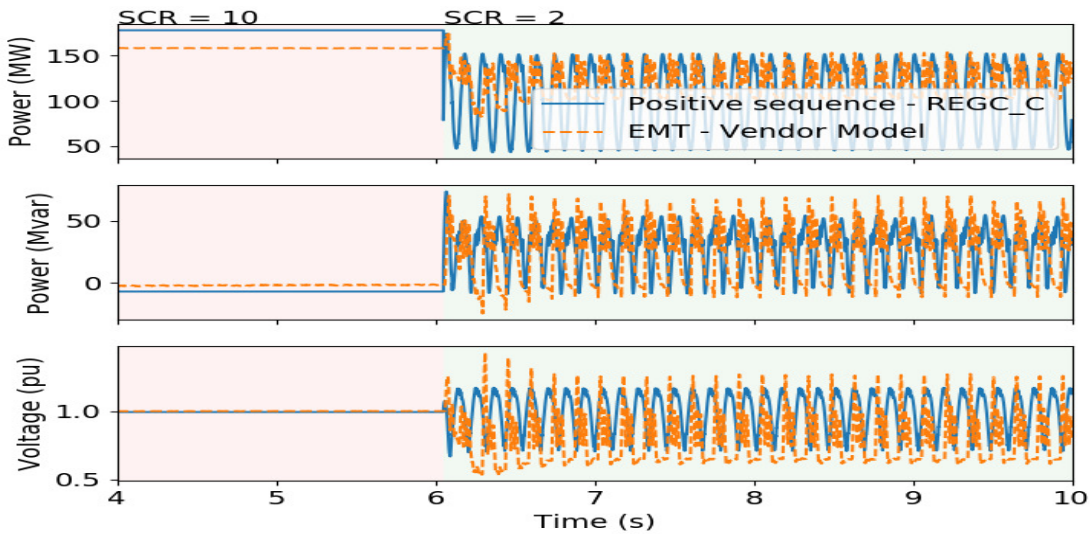


Figure 16: With reduction in SCR and with pre-disturbance operation at 0.9pu in the positive sequence model, comparison of response between black box EMT model and positive sequence REGC\_C generic model of solar plant in South Texas

into the black box model. As a result, the parameter values that are derived must be validated by the OEM/plant developer. However, since this model is expected to be parameterized and provided by the OEM/plant developer at the outset using their best practices, it is expected that as the use of the model becomes more common, more

accurate parameter values will be available.

## 5. Conclusion

In this paper, using numerous examples, it has been demonstrated that the newly developed REGC\_C generic positive sequence model can provide indication of unstable/oscillatory behavior observed when IBRs are connected at locations of low short circuit strength. Once tuned appropriately, the performance of this model is superior to the existing state-of-the-art REGC\_A model which is unable to provide the same level of fidelity. Further, the paper provides a conceptual approach to translate values of controller gains from the EMT to the positive sequence domain. It must however be cautioned that this conceptual approach can be challenging if there are substantial differences in control topology across both simulation domains. Validation of this new model behavior with respect to actual equipment around the world further shows the benefit of this model. The development of new and improved positive sequence generic models is not intended to replace detailed EMT simulation studies. Rather, improved positive sequence models can provide additional insight into the behavior of IBR from positive sequence simulations while helping to better focus the scope of detailed EMT simulations.

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### **Highlights of paper**

1. Showcase the ability of improved positive sequence inverter resource models to represent oscillatory behavior observed in power systems
2. Illustrate the importance of parameterization of the generic positive sequence models.
3. Illustrate the possibilities of extending the applicability of positive sequence simulation tools for stability studies of larger power systems.

### **Credit Author Statement**

**Deepak Ramasubramanian:** Conceptualization, Methodology, Software, Validation, Writing – Original Draft. **Xiaoyu Wang:** Writing – Review & Editing. **Sachin Goyal:** Writing – Review & Editing. **Manjula Dewadasa:** Writing – Review & Editing. **Yin Li:** Writing – Review & Editing. **Robert J. O’Keefe:** Writing – Review & Editing. **Peter F. Mayer:** Validation, Writing – Review & Editing

## **Declaration of interests**

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: