Development and Implementation of Short Circuit Models for Wind Turbine Generators

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***Abstract*— The proprietary control of the power converters used to interface wind turbine generators (WTGs) with the power grid causes a nonlinear response to faults from Type III and Type IV WTGs. The conventional models representing synchronous generators for phasor domain short circuit analysis are linear, and therefore need to be significantly revised. Working group C24 of the Power System Relaying and Control (PSRC) Committee explored this problem with the help of several major stakeholders and came up with new models and recommendations. This paper summarizes the work. Models proposed by the working group are described. Implementation details of these models by EPRI and three major software vendors are summarized. Comparison of results using the implementations are presented.**

***Index Terms*—Fault Calculation, Inverter, Phasor Domain Modeling, Short-Circuit, Wind Turbine Generator**

I. Introduction

Phasor domain short circuit study is an essential step in integrating new generation facilities into the system, as it informs the selection of switchgear and setting of protective relays. Due to the linear response of synchronous and induction generators to faults, the formulation of short circuit calculations is based on linear system models in phasor domain. However, generation that connects to power systems fully or partially through inverters has highly nonlinear response to faults. Type III and Type IV wind turbine generators (WTGs) belong to this category.

Working group (WG) C24 was formed in the IEEE Power System Relaying and Control Committee (PSRC) to investigate models for such generators that could be incorporated in the commercial phasor domain short circuit programs used extensively by utilities and industries in North America and across the world. The working group had representation from various manufacturers of WTGs, developers and vendors of commercial short circuit programs, utilities, relay manufacturers, consultants, academia, and Electric Power Research Institute (EPRI), a prominent research and development arm of North American utilities.

The challenging aspect of the WG assignment was to develop methods that yielded reasonably accurate models for WTGs which can be incorporated within the existing commercial short circuit programs, despite the proprietary controls of WTGs that are not available in public domain. This paper summarizes the development of such models and describes how the models were adopted and validated by EPRI and three major commercial short circuit program vendors in North America. Section II provides a background of the response of WTGs to power system faults, emphasizing the need for new short circuit models. Section III describes the proposed models. Sections IV and V provide details of implementation and validation of these models. Section VI provides concluding remarks.

II. Fault Response of Wind Turbine Generators

There are primarily four types of WTGs in use: Types I, II, III & IV. Response of Type I & II to faults on the AC network is dictated by the electromagnetic configuration of the rotating generator, and the response of Type III & IV is dictated by controls that direct how the power electronics in the WTG respond to the reduced voltage on the terminals of the machine caused by the fault.

A. Type I and Type II

The Type I and II WTGs are induction generators. The Type I has a squirrel cage rotor, and the Type II has a wound rotor. Both types have similar responses to faults which are controlled

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by the electromagnetic configuration of the induction generators. Equation (1) can be used to calculate the equivalent transient reactance X' for the WTG. This reactance can be used in the fault study program to calculate the maximum current that the WTG could contribute to a fault on the AC network it is connected to.

$$X' = X_s + \frac{X_m X_2}{X_m + X_2} \qquad (1)$$

In (1), X_s is the stator leakage reactance, X_m is the magnetizing reactance, and X_2 is the rotor leakage reactance referred to the stator.

B. Type III & Type IV

In the Type IV WTG, the rotating generator is electrically isolated from the AC network through an electronic converter. In this configuration, the response of the Type IV WTG to a fault on the AC network is totally dictated by the controls for the power electronics of the converter.

The Type III WTG has a wound rotor induction generator with the stator windings connected to the AC network but the rotor field being supplied from a rotor side converter (RSC) connected to a grid side converter (GSC). Therefore, the response of the Type III WTG is dictated by both the electromagnetic configuration of the rotating generator and the controls for the power electronics. The initial response of the Type III WTG to a fault is due to the electromagnetic configuration of the generator, but this initial response is quickly overcome by the response of the power electronics. What happens next depends on the severity of the fault. A protective action could be triggered in the rotor circuit depending on the level of induced current in the rotor circuit and the rating of the power electronic components. This protective action will short the terminals of the induction generator's rotor windings. In the rotor shorted state, the induction generator will respond like a Type II WTG. The shorted state will not be maintained, so the response will return to the controlled electronic state.

All WTGs, regardless of the type, need to meet the grid codes of the network to which they are connected. These grid codes vary, but they all require that the WTGs do not disconnect for a fault on the network where the isolation of that fault does not necessitate the shutdown of the WTG. This common requirement is called low voltage ride-through (LVRT). The WTG's controls are equipped to keep the WTG operating during the low voltage caused by the fault if it is cleared in a reasonable time. The action the WTG takes to ride though the low voltage is fast and, in most cases, results in the injection of reactive power to raise the voltage in the electrical vicinity of the WTG. This voltage rise permits real power to flow from the WTG, facilitating the ride through. As a result, the response of the WTGs for faults on the AC network is influenced by the response to meet the LVRT requirements. The power electronics of the WTG may not be able to sustain the level of current called for in the initial control response, so the controls ramp back the response to current levels slightly greater than the nominal rating for the WTG. Since most faults on the transmission networks are detected by relays in less than 2 cycles and the faults are cleared in about 5 cycles, the response of the WTGs during the initial period is critical.

TABLE 1. PROPOSED DATA REQUIREMENTS TO CREATE PHASOR DOMAIN SHORT CIRCUIT MODELS OF WTGS.

Time frame 1 (seconds or cycles)		**Fault Type:**
Positive-sequence voltage $V^{(1)}$ (pu)	**Positive-sequence current $I^{(1)}$ (pu)**	**Angle of $I^{(1)}$ with respect to $V^{(1)}$**
1.0		
0.9		
0.8		
0.7		
0.6		
0.5		
0.4		
0.3		
0.2		
0.1		

III. MODEL PARAMETERS REQUIRED TO MODEL TYPE III AND TYPE IV WIND TURBINE GENERATORS

As described in section II, the fault response of Type III and Type IV WTGs is nonlinear and highly dependent on the proprietary controls not available in public domain. As with any nonlinear element, the output characteristics, i.e., the relationship between the element's voltage and current, would need to be determined through an iterative process. This is within the scope of the commercial programs. How to obtain the output characteristics is the key question. The WG came up with two models described as follows.

A. Generator Output based Model

In this most general model, it is recommended that the WTG manufacturers provide a tabular output of positive and negative sequence voltages, currents, and power factors at the machine terminals. This would enable the machine to be modeled as a non-linear voltage controlled current source (VCCS). Also, since the output varies for a few cycles after a fault, depending on how quickly the control takes over, it is appropriate that the tables be provided for various time-frames (e.g., 1 cycle, 3 cycles, 5 cycles). If the output to a given fault depends on the control mode of the WTG, the tables need to be provided for each control mode. Finally, the pre-fault output at which the data are generated needs to be specified – typical practice would be to keep the pre-fault power at a rated value. Table 1 shows the details of the required positive sequence data for this model. Note that the second and third columns of the table are intentionally blank to indicate the values recommended to be provided by the WTG manufacturer. A similar table is to be provided for negative sequence quantities. Also note that WTGs do not generate zero-sequence currents.

The data required to fill out the table may be obtained using a variety of methods listed below.

- The inverter manufacturer may provide the table although it may not always be straightforward to obtain the manufacturer's data.
- Another method to generate the data is to use detailed electromagnetic transient (EMT) simulations based on an equipment specific (typically black box) EMT model of the WTG. In this method, a simple network can be used, and a fault can be placed at the inverter terminals. Different voltage magnitudes can be produced by changing the resistance of the fault. For each simulated voltage magnitude, current injection of the inverter and the power factor are obtained. The applicability of this method is contingent on availability of an equipment specific EMT model of the WTG.
- In the absence of manufacturer's data and adequate EMT models, another method to parameterize the VCCS model is to use generic algorithms for generic inverter control modes.

B. Generic Control Parameter based Model

This model is to be used if the tabular data for the output-based model is not available. This model is built on generic controls developed by EPRI that have been validated against some field data. However, the data gathered by the WG from various WTG manufacturers [1] show that this approach does not guarantee accurate models for all makes and models of WTGs. On the other hand, it is easy to implement and integrate with existing commercial programs.

IV. Implementation Algorithms For Type III and Type IV Wind Turbine Generator Models

Both the generator output-based and generic control parameter-based models are generally nonlinear and need iteration with a network solver. Figure 1 shows a flowchart of the iterative process. The WTG model (marked by a red dashed box) calculates the WTG output current I_{WTG} as a function of terminal voltage V_{WTG}, either using a table (for the generator output-based model) or based on generic equations (generic control parameter-based model). The starting point of the iteration is an initial estimate for V_{WTG} which can be obtained from a power flow solution. Based on this initial voltage, the WTG short-circuit (SC) model calculates I_{WTG} and injects it into the network. Then, the network solver uses the injected current to update V_{WTG} for the next iteration step. The iteration continues until the network voltage and WTG current injections settle.

The following subsections present the Type III and IV WTG models and implementation algorithms developed by EPRI and three major software vendors.

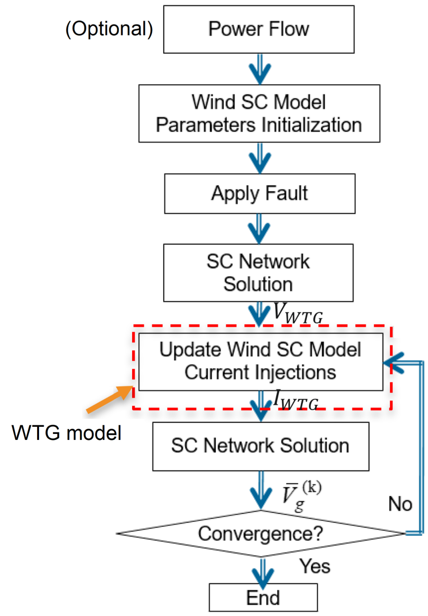


Figure 1. Iterative solution of Type III and Type IV WTG short circuit model using network solver.

A. EPRI

EPRI in collaboration with Polytechnique Montreal has developed phasor domain steady-state short-circuit (SC) models for wind plants employing Type III [2] and Type IV WTGs [3]. As shown in Figure 2, the WTG has been represented by a VCCS (red dashed box) at the low voltage side of the wind turbine transformer. The voltage dependency of current is expressed in terms of a set of equations representing generic control modes/logic of the WTG and considering control nonlinearities. The iterative solution uses the flowchart of Figure 1. The model calculates both positive- and negative-sequence fault current components of a WTG. The developed models have been benchmarked against generic EMT-type WTG models validated using some fault records [1].

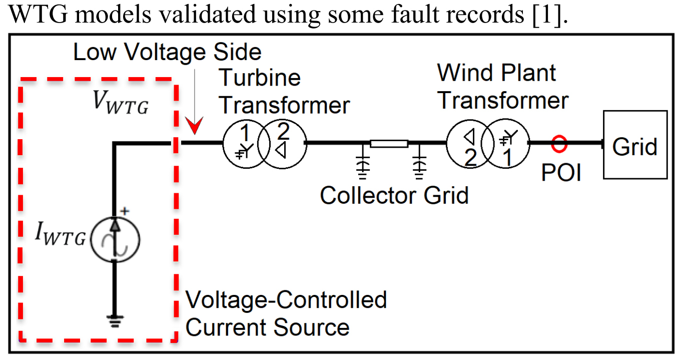


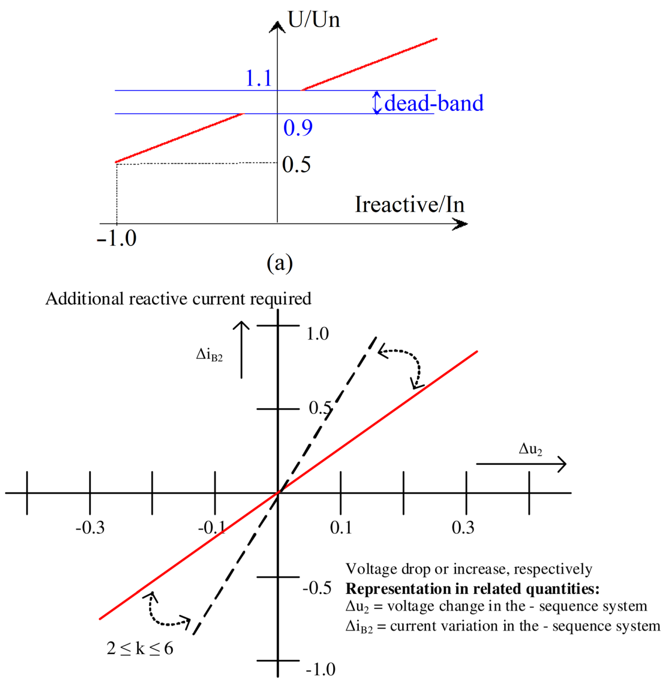
Figure 2. EPRI model for Type III WTG and Type IV WTG.

Table 2 presents the generic control modes and control priority options. The control setpoints are applied at the low voltage side of wind turbine transformer.

Figure 3 (a) shows a typical curve for the positive-sequence dynamic current control. In this figure, the additional reactive current required is proportional to the voltage deviation from nominal voltage (U_n) when voltage falls outside a defined dead-band. Figure 3 (b) presents negative sequence reactive current injection based on VDE-AR-N 4120 Technical Connection Rules [4].

TABLE 2. GENERIC CONVERTER CONTROL MODES OF A WTG.

Function	**Control Mode**	**Performance Description**
Reactive power/voltage control during ride-through	Reactive power control	Enables fixed desired injection/absorption of reactive power
	Power factor control	Enables injection/absorption of reactive power based on a desired power factor
	Voltage control	Enables control of voltage at desired setpoint
	Dynamic reactive current control (also known as Fault Ride-Through (FRT))	Enables positive and negative sequence reactive current injection based on a reference curve (e.g., grid code)
	Control Priority	**Performance Description**
	Active current priority (P-priority)	The active current output is given priority and the reactive current output is constrained to the remaining current capacity.
	Reactive current priority (Q-priority)	The reactive current output is given priority and the active current output is constrained to the remaining current capacity.



(b)

Figure 3. Dynamic reactive current control curve for (a) positive sequence reactive current and (b) negative sequence reactive current based on VDE-AR-N 4120 Technical Connection Rules [4].

1) Type IV WTG Model

Given that Type IV WTG is interfaced to the grid through a fully sized converter, the fault response is dictated by the GSC. The EPRI model has been developed based on a generic GSC control scheme assuming dq-frame control. The scheme consists of three main stages: (i) an outer voltage control loop which regulates the dc- and ac-side voltages by generating *desired* current setpoints; (ii) a current limiter which constrains these desired current setpoints based on a current limiting logic and "P or Q priority", and provides *actual* current setpoints to an inner current control loop; and (iii) an inner current control loop which regulates the converter terminal ac voltage such that the terminal currents follow the provided actual setpoints.

During a fault, the active power injection is influenced by wind speed and maximum power tracking control whereas the reactive power injection mainly depends on the control mode. The EPRI model represents the GSC control scheme using a set of equations which calculate low-voltage (LV) bus positive- and negative-sequence current phasors based on positive- and negative-sequence LV bus voltage phasors. Excess active power during fault is dissipated by a chopper protecting the dc link capacitor.

2) Type III WTG Model

The EPRI Type III WTG model assumes RSC and GSC control through vector control techniques. The RSC regulates the active and reactive powers supplied to the grid via adjusting generator speed for optimal power generation at various wind speed levels. The RSC control of the Type III WTG model uses the same control modes and generic control schemes as those of the GSC of the Type IV WTG model. The GSC control of Type III WTG regulates the dc bus voltage and may be used to provide reactive power support to the grid during a fault.

The fault current response is determined by the combined and coupled response of the induction generator (IG), RSC, and GSC. The fault current consists of IG stator current contribution and the GSC current contribution and is computed in three steps [3]:

- First, the stator current phasor is computed based on active power generation and the control mode of the WTG. To verify that the corresponding rotor currents conform to the RSC current limits, the calculation of stator currents is performed by first calculating the *desired* rotor currents, then applying the RSC current limits and calculating the *actual* rotor currents, and finally translating the actual rotor currents into corresponding stator currents.
- Next, the GSC current phasor is computed based on the active power flow in the RSC (calculated from the calculated rotor and stator current) and potentially needed reactive power support from GSC.
- Finally, the overall fault current is computed as the vector sum of the stator and GSC currents.

A challenge is to properly represent the fault response of a Type III WTG under an unbalanced fault considering the coupling between the negative-sequence parameters of the RSC and the positive-sequence active power of the GSC. The EPRI model represents this coupling by considering the effect on the GSC active current [3].

B. ASPEN OneLiner

ASPEN's short circuit program is based on a solution method by [5]. The VCCS model described in Section III was integrated with this program. Each VCCS bus was treated as an "active bus". In each iteration, a current of a certain magnitude and angle is injected based on the latest terminal voltage magnitude and the angle of the voltage phasor. The calculation is iterative because each time the current injection is updated, the terminal voltage of the VCCS terminal changes, and that, in turn, may call for a different current magnitude and power-factor angle.

This method works well in most cases, but it does not always converge. Consider this example. The user applies a 3-phase fault with 4 ohms of fault resistance in front of the converter's unit transformer. Suppose the power-factor angle in the VCCS table for a low terminal voltage is -90 degrees. The actual power-factor angle from the short circuit solution, however, is between -90 degrees and 0 degrees due to the resistance of the short circuit path.

Therefore, the convergence criterion has to be flexible to tolerate a finite difference between the actual power-factor angle and the desired power-factor angle. In the short circuit program, the solution is considered converged when the change in the power-factor-angle and the terminal voltage magnitude for WTGs and the change in the terminal voltage magnitude and angle at other network nodes between two successive consecutive iterations fall within a certain threshold.

The VCCS model proved to be difficult to use for some users because the required data from manufacturers were not available to more than half the users in this initial period. This may change as the contents of this WG become better known. To address this issue, in a major release of the short circuit program in 2021, a more user-friendly model called the "Converter-Interfaced Resource" was created that requires less data input and, at the same time, encourages aggregation of units. In addition to the injection of positive-sequence reactive current, this model can inject negative-sequence current for unbalanced faults, as required by the latest German grid code [4] and shown in Figure 3. This feature requires only one additional input: a parameter known as the "negative-sequence slope". The negative-sequence current injection is 90 degrees ahead of the negative-sequence voltage phasor, with a magnitude equal to the slope times the per-unit magnitude of the negative-sequence voltage phasor. The Converter Interfaced Resource is capable of modeling not only Type IV wind plants, the focus of this paper, but also solar plants and battery storage systems. The VCCS model is used to model STATCOM and other custom control schemes.

In the same release in 2021, there is a model created specifically for Type III wind plants, created from the EPRI model described in Section IV-A-2. This model accounts for the electrical parameters of the induction machine, the torque-versus-slip characteristics of the wind-turbine blades, as well as the workings of the back-to-back converters that control the rotor current. Current limiting is achieved by limits on d- and q-axis rotor currents in the GSC and the RSC. This model also encourages the aggregation of units and can be used in crowbarred mode by simply marking a checkbox in the corresponding dialog box. When crowbarred, the model acts as a passive induction machine that outputs in the order of 4 to 5 times the full-load current. When the Type III WTG is under automatic control (i.e., not crowbarred), the current is typically limited to no more than 1.5 times the rated current, and both positive- and negative-sequence currents are present in the output for an unbalanced fault.

After several years of experience with these models, some common factors that contribute to *non-convergence* have emerged as listed here.

1. Pre-fault voltages were used from a flat-start or "classical condition". It is paramount that the pre-fault voltages are calculated from an Ohm's-law solution that takes into account phase shifts.
2. Real power is output by the models when there are no loads in the network.
3. A transformer and/or lines that carry the power from the models to the network are not sufficiently rated.
4. The unit transformer is missing. Each of these device models – that represents either a single physical device or an aggregate – has to be connected to the network through the wye winding of either a wye-delta or wye-wye-delta transformer.
5. Multiple units are connected through branches with very low impedance. Aggregating the units should solve this problem.

C. ETAP

1) WTG Types I, II and III with crowbar

WTG Type I and Type II are modeled as an induction generator. WTG Type III is also modeled as an induction generator when the crowbar is set to be active. Crowbar and chopper resistance is a settable quantity in this case.

2) WTG Type III without crowbar and Type IV

The same model is used for WTG Type III without the crowbar, WTG Type IV as well as other inverter-based resources (IBRs) such as solar and battery. In this section, the term IBR is used to represent all of them. In ETAP, the VCCS is used to model IBRs. For a user-defined fault, current curve/lookup tables, control logic or black-box model, ETAP User-Defined Model, IBR Application Programming Interface (API) or Co-simulation with PSCAD can be used within the transient stability study to fully analyze IBR response during a fault or other disturbances.

Within a short circuit study, positive- and negative-sequence current injection is used to model IBRs. The magnitude and angle of injected I_1 and I_2 are defined based on several factors. First, the magnitude of phase current is limited by a curve as shown in Figure 4 regardless of IBR control strategy. This is to accommodate IBRs with variable phase current limit depending on their terminal voltage. If IBR maximum short circuit current is independent of voltage, the curve parameters can be properly selected to achieve that.

In ETAP, three control strategies are supported including 1-Reactive Current Priority, 2- Active Current Priority, and 3-User-defined Power Factor. In reactive current priority, it is initially assumed that the active current contribution, i.e. I_{d1}, is zero, and I_{q1} and I_2 are calculated from the FRT curves as shown in Figure 5 and the following equation.

$$\begin{aligned} I_{q1} &= jK_1 \times (|V_{1fault}| - |V_{1pre\text{-}fault}|) \\ I_2 &= I_{d2} + jI_{q2} = K_2 \times (|V_{2fault}| - |V_{2pre\text{-}fault}|) \angle(\theta_{I2Ang} - \angle V_{1fault}) \end{aligned} \quad (1)$$

where K_1 and K_2 are positive and negative sequence slopes of the FRT curve, respectively; $dV1 = |V_{1fault}| - |V_{1pre\text{-}fault}|$ and $dV_2 = |V_{2fault}| - |V_{2pre\text{-}fault}|$. θ_{I2Ang} is the angle by which I_2 leads V_2. I_{d2} and I_{q2} are direct and quadrature components of negative sequence current, i.e. I_2. This angle can be set by users, and default is 90^0. It is important to note that negative sequence current injection is optional and can be disabled. Both currents are with reference to positive sequence voltage, i.e. V_1. To verify that phase currents do not exceed short circuit limit, phase currents are calculated from I_{q1} and I_2. If the limit is exceeded, I_{q1} and I_2 are reduced in equal proportions to meet the limit. On the other hand, if there is any room left for active power injection, active current I_{d1} is increased based on the pre-fault power flow results without exceeding the phase current limits. Since IBR power flow and short circuit limits are close, ETAP does not ignore active current injection in short circuit analysis.

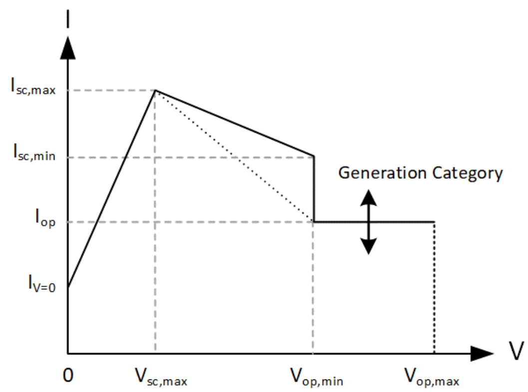


Figure 4. Phase short circuit current limit

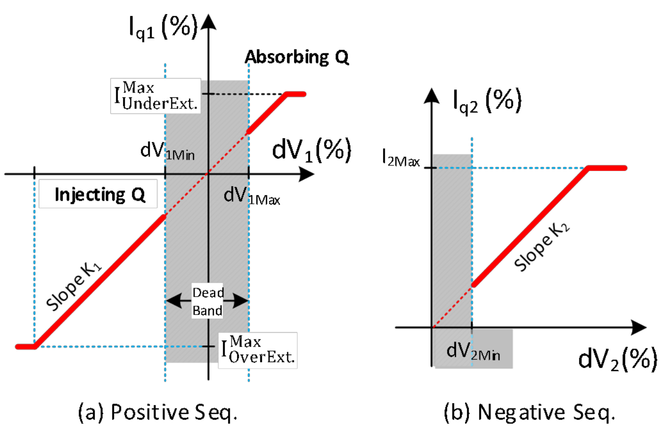


Figure 5. IBR current injection characteristic

In the active power priority mode, negative-sequence current injection is not available. In this case, firstly, the active power current I_{d1} is calculated based on the pre-fault active power, while it is limited to IBR maximum short circuit current at the calculated voltage. If the limit is not reached, reactive current I_{q1} will be added as per the FRT curve shown in Figure 5 (a) up to the short circuit limit.

The user-defined power factor mode is similar to the active power priority mode except that the reactive component is based on the user-defined value instead of the FRT curve.

Within iterative short circuit calculations, after first few iterations, i.e. settable by user, if positive-sequence voltage falls below $V_{op,min}$ as shown in Figure 4, it is assumed that the IBR has initiated FRT support. Hence, the dead-band shown in Figure 5 and normal operation region shown in Figure 4, between $V_{op,min}$ and $V_{op,max}$, is eliminated, and the FRT curve and the short circuit current limit curve become continuous.

In order to avoid non-convergence especially when an IBR is connected to a weak system or there are many IBRs in the system interacting, after first few iterations, IBR calculated currents, i.e. I_1 and I_2, are passed through a rate limiter function, representing IBR series inductor. Furthermore, an additional filtering is applied to calculated voltages within iterations for FRT calculation, representing digital filters used in IBR controller, to avoid unstable or undamped oscillations between two or more solutions.

In all three modes of operation, there is a possibility that injected current cannot flow into the system due to system characteristics and limitations in transferring certain amount of active or reactive power. In this scenario, the injected IBR current considerably impacts its own terminal voltage, leading to non-convergence of the solution. What the actual IBR controller does in such scenarios depends on the IBR controller algorithm and may vary from one to another. In IBRs, phase angle reference is determined by the phase lock loop that is typically locked in these situations. ETAP provides a logic resembling what happens in most common IBRs to lock the reference angle to the pre-fault angle if voltage drops below a preset value or a rotatory angle is detected at an IBR terminal during iterations.

D. PSS®CAPE

This section summarizes the PSS®CAPE steady-state phasor models of IBR. PSS®CAPE models the inverter to predict fault contribution and relay currents in the network. The current phasors are the controlled response to a constant power source at the network frequency after the initial transient, about 2 cycles after the fault. The implementation includes three types of IBR models: Type IV, Type III, and VCCS. These models can be used for batteries, solar, and wind systems. The solution is obtained in an iterative computation that addresses the nonlinear behavior of the power converter.

Type IV WTG model in PSS®CAPE is configured as a VCCS that injects a positive-sequence current in the system. The total power generated by the WTG passes through the power converter. PSS®CAPE models the generator from the low-voltage to the medium-voltage side. The LV-MV transformer and the filter are modeled within the WTG model; the collector grid and the medium-voltage to high-voltage transformer are modeled separately in the database. As developed by EPRI, the model includes four modes of control: desired reactive power, desired power factor, desired voltage magnitude, and reactive current injection proportional to the voltage deviation (FRT). A future development contemplates implementing the negative-sequence current control. The magnitudes of the controlled currents are limited to specified values: typically, 1.0 to 1.2 pu on the machine voltage and MVA bases.

The Type III model is based on the ANAFAS model [6,7], where the negative sequence currents are suppressed. The doubly-fed induction generator (DFIG) is treated as a conventional synchronous generator with a chosen current limit. For currents below the limit, the internal impedance and EMF are fixed. The EMF depends on the initial load current.

If any phase current reaches the limit, the three phase currents become constant. The model includes the generator's internal impedance and computes the current into the network from each generator. At the current limit, the model injects a constant current with an infinite shunt impedance, keeping the proportions of the postfault phase currents fixed in magnitude and angle. Otherwise, if all phase currents are less than the limit, the generator is treated as a conventional synchronous generator with a fixed EMF with an internal impedance (a linear device). Type III also supports the "crowbar" option in which the generator is modeled as a synchronous generator, without any limit. The positive-sequence control for this type is currently under development.

In the VCCS model the desired solution is supplied by the PSS®CAPE user as tables of current and power-factor angle values versus the generator voltage at the medium-voltage bus, as described in Section II. The lowest current magnitude corresponds to either a remote fault or to a 1.0 p.u. voltage at the generator. A negative power-factor angle implies that the current into the network lags the bus voltage by between 0 and 180 degrees. Only positive-sequence values are adopted in this model.

PSS®CAPE uses the following algorithm to calculate the current contribution from wind plants to the network:

- Loop through all the plants in the system.
- Remove any isolated generators from the network.
- For Type IV only, calculate pre-fault orthogonal component currents (Id, Iq) from the pre-fault voltage and specified reference power (P, Q).
- For subsequent iterations, apply the controls and inject the controlled fault currents into the network.
- Test for convergence after a predefined number of iterations.
- Compute the positive-sequence voltage and current in the external network.

An option lets the program remove generator currents for a remote fault. For a given faulted bus, the program will ignore the generator if the initial generator bus voltage Vpu is close to its prefault value, for example if $0.99 < \text{Vpu} < 1.01$, with the generator temporarily removed. In the real network, the generator current is dissipated in nearby loads, but those loads may not be in the short circuit database.

If the inverter controls cannot produce a fault current contribution, it is most likely due to a convergence issue. In general, if there is no infeed current between the generator and the fault, the solution may not converge. For example, at a zero-voltage faulted bus, the voltage phase angle is undefined, so the computed current can take any phase angle relative to the network. To improve the convergence of the model, PSS®CAPE has implemented the following logic upon discussions with EPRI:

- If the IBR is isolated from other sources, PSS®CAPE does not attempt to solve it.
- The changes of the fault current contribution phase angle at successive iterations are smoothed by interpolation.
- If the apparent impedance, calculated as the ratio of the positive-sequence voltage over current at the LV grid-side converter, is constant (but not zero) in the first three iterations, the IBR is considered islanded. Then PSS®CAPE keeps the positive sequence voltage angle at its prefault value.
- If the number of iterations has reached its maximum, the control will be switched to "Iq-injection" for a further series of iterations. Now, the injected current lags the voltage by 90 degrees, and the current magnitude is increased to its limit or to the value in the table for the voltage (VCCS).

V. Model Validation

To verify consistent implementation of the models and methods described in Section IV, a software-to-software cross-examination test has been conducted using a 120kV test system shown in Figure 6. The system embeds a wind plant consisting of 45×1.5 MW Type IV WTGs operated under FRT control with Q-priority. The plant is interconnected to the power grid at BUS1 and has been represented by an aggregated plant model which represents the 45 WTG units by one equivalent unit. The collector grid has been represented by an equivalent PI section. The rated voltage of the turbine system and the collector grid are 0.575 kV and 34.5 kV, respectively. A 0.575kV/34.5kV turbine transformer connects the WTG units to the collector system. The low side of the turbine transformer is hereinafter referred to as LV, and high side is referred as medium voltage bus (MV). A 34.5kV/120kV transformer connects the collector system to the transmission level voltage.

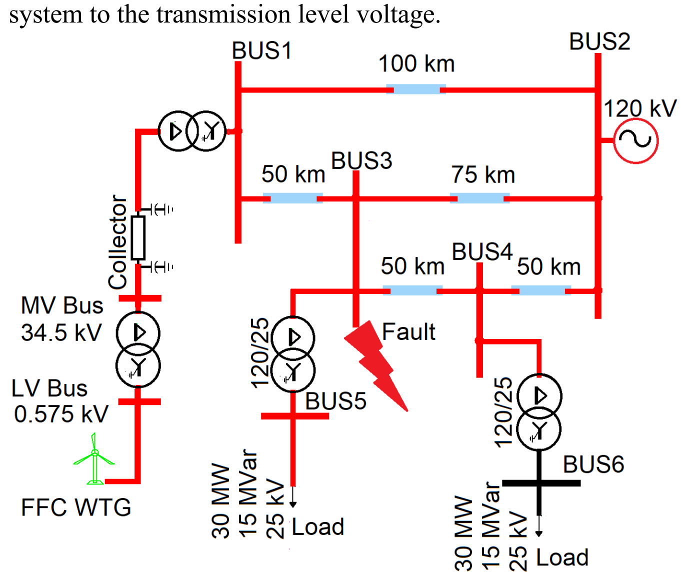


Figure 6. Test system for cross-examination of WTG SC model implementations.

The following implementations of the test system have been cross-examined:

1. An ASPEN OneLiner implementation representing the WTGs by a VCCS table placed at LV;
2. A PSS®CAPE implementation representing the wind plant by a VCCS table placed at LV;
3. A PSS®CAPE implementation representing the wind plant by the "EPRI TYPE-IV WTG" model;
4. An ETAP implementation;
5. An algorithm code developed by EPRI representing both the network and the wind plant as a set of equations solved

iteratively; and

6. An EMT implementation within EMTP which uses a detailed generic EMT model of the wind plant including control schemes, power electronics and hardware. Due to the high level of modeling details, this EMT model can potentially provide the highest accuracy [8].

The VCCS tabular model data in implementation number 1, 2, and 3 have been generated using the EPRI model described before. The tabular VCCS model consists of 10 rows corresponding to voltage amplitudes between 1.0 pu and 0.1 pu in steps of 0.1 pu.

TABLE 3. COMPARISON OF MODEL IMPLEMENTATIONS OF SECTION IV.

Quantity	Implementation	3Ph-G Fault on BUS 3		ABG Fault on BUS 3	
		Mag	Ang (deg)	Mag	Ang (deg)
V1_LV (pu)	ASPEN VCCS LV	0.50	0.00	0.70	0.00
	CAPE VCCS LV	0.49	0.00	0.70	0.00
	CAPE (EPRI TYPE-IV WTG)	0.50	0.00	0.73	0.00
	ETAP	0.50	0.00	0.71	0.00
	EPRI Code	0.50	0.00	0.71	0.00
	EMTP	0.50	0.00	0.71	0.00
I1_LV (A)	ASPEN VCCS LV	85940	-66.80	85484	-35.70
	CAPE VCCS LV	85864	-66.80	85444	-35.30
	CAPE (EPRI TYPE-IV WTG)	85950	-64.85	85448	-32.64
	ETAP	85948	-66.24	85487	-34.53
	EPRI Code	85948	-65.67	85492	-34.60
	EMTP	85906	-66.03	85491	-33.95
V1_MV (pu)	ASPEN VCCS LV	0.45	-32.40	0.67	-33.70
	CAPE VCCS LV	0.43	-32.70	0.67	-33.80
	CAPE (EPRI TYPE-IV WTG)	0.45	-32.41	0.70	-33.66
	ETAP	0.45	-32.68	0.68	-33.85
	EPRI Code	0.45	-32.71	0.68	-33.80
	EMTP	0.45	-32.54	0.68	-32.91
I1_MV (A)	ASPEN VCCS LV	1432	-96.80	1425	-65.70
	CAPE VCCS LV	1431	-96.80	1424	-65.30
	CAPE (EPRI TYPE-IV WTG)	1432	-94.81	1423	-62.66
	ETAP	1432	-96.24	1425	-64.53
	EPRI Code	1432	-95.96	1425	-64.60
	EMTP	1414	-96.03	1425	-63.95

Table 3 presents the results of a three-phase-to-ground fault and a phase-A-to-B-to-ground fault on BUS 3 showing the positive-sequence voltage at the LV bus (V1_LV), the positive sequence current from the LV bus to the grid (I1_LV), positive-sequence voltage at the MV bus (V1_MV), and the positive sequence current from the MV bus to the grid (I1_MV). The phase angles have been expressed with respect to V1_LV. The results have been obtained 5 cycles into the fault when the response has reached a steady state condition. The results suggest an acceptable agreement between the implementations. A few small inconsistencies exist which are due to the low granularity of the VCCS table data (10 rows). Conducted simulations suggest that the accuracy may be improved by increasing the data granularity. The EMT implementation has been used as reference for accuracy comparison. The initialization method and assumed pre-fault WTG operating point further have an impact on the accuracy of results. Similar results were obtained for other fault types as well.

VI. CONCLUSION

This paper describes new models and methodologies to incorporate the short circuit response of WTGs in phasor domain short circuit programs. It shows how the output response can be tabularized for the most general representation of the fault response. It also describes a generic model in case the data are not available from the manufacturer, though using such a model does not guarantee the most accurate results for every make and model of WTGs. The VCCS tabular model can also be used to model IBR plants based on solar inverter systems as they are also full converter based resources. The paper also highlights, among other details, practical issues with non-convergence and how the issues can be circumvented. Results generated by various software programs for a given test system show consistent performance of model-implementations across all software platforms. This work provides the foundational basis for short circuit analysis of systems with IBRs. Additional insights and modifications will continue to be formed based on feedback from users. A new working group C45 is formed in the PSRC to incorporate such modifications.

VII. REFERENCES

[1] "Modification of commercial fault calculation program for wind turbine generators," IEEE Power & Energy Society, Report PES-TR78, 2020.

[2] T. Kauffmann, U. Karaagac, I. Kocar, S. Jensen, J. Mahseredjian and E. Farantatos, "An Accurate Type III Wind Turbine Generator Short Circuit Model for Protection Applications," *IEEE Trans Power Del.*, vol. 32, no. 6, pp. 2370-2379, Dec. 2017.

[3] T. Kauffmann, U. Karaagac, I. Kocar, S. Jensen, E. Farantatos, A. Haddadi, and J. Mahseredjian, "Short-Circuit Model for Type-IV Wind Turbine Generators With Decoupled Sequence Control," *IEEE Trans. Power Del.*, vol. 34, no. 5, pp. 1998-2007, Oct. 2019.

[4] "Technische Regeln für den Anschluss von Kundenanlagen an das Hochspannungsnetz und deren Betrieb (TAR Hochspannung)," VDE-ARN 4120 Anwendungsregel: 2018-11, 2018.

[5] V. Brandwajn and W.F. Tinney, "Generalized Method of Fault Analysis," IEEE Trans. On Power Apparatus and Systems, pp. 1301-06, June 1985.

[6] Anafas Analise De Faltas Versio 6.5.1 Manual Do USARIO, CEPEL - Centro de Pesquisas de Energia Eletrica, Rio de Janeiro, Brasil; Marco, 2014.

[7] Sergio P. Romero et. al. (CEPEL), "Representacao de Geradores Eolicos Sincronos com Conversor de Frequenca por Fontes de Corrente Controladas em um Programa de Calculo de Curtos Circuitos," XI Symposium of Specialists in Electric Operational and Expansion Planning, Brasil; March 2009.

[8] U. Karaagac, J. Mahseredjian, R. Gagnon, H. Gras, H. Saad, L. Cai, I. Kocar, A. Haddadi, E. Farantatos, S. Bu, K. W. Chan, and L. Wang, "A generic EMT-type model for wind plants with permanent magnet synchronous generator full size converter wind turbines," IEEE Power and Energy Technology Systems Journal, vol. 6, no. 3, pp. 131–141, Sep. 2019.