Validity Range of Fundamental Frequency Simulations under High Levels of Variable Generation Technologies

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Abstract- **The high complexity of realistic-size power systems have led to simplified stability studies in order to obtain the system dynamic response under contingencies within acceptable computational time and resources. In these studies, also known as Transient Stability (TS) assessments, simplified fundamental frequency (FF) simulations are carried out based on the assumption that fast transients do not affect system stability. In this context, this paper aims to verify the validity range of traditional TS studies in power systems with high levels of converted-based variable generation technologies (VGTs). To do this, first, a detailed modal analysis is carried out to understand the evolution of the system's modes as VGTs increases. Then FF and detailed electromagnetic simulations are performed considering different penetration levels of VGTs. Simulations are carried out in the IEEE 9-bus system using DIgSILENT Power Factory.**

***Index Terms*— dynamic performance, EMT simulations, power system stability, RMS simulations, stability assessments.**

I. Introduction

POWER system stability has been recognized as one of the key issues for a secure power system operation for almost a century [1]. To prevent the system from losing stability and cascading effects leading to major blackouts, regulators and Transmission System Operators (TSOs) regularly perform different stability studies in order to detect hazard situations and thus define corrective measures aiming to maintain system integrity during extreme contingencies. By this way, the economic consequences in the society can be minimized.

To assess power system stability, the dynamic phenomena related to the different system components must be modelled and their joint operation must be simulated. The transient response of a power system ranges from fast (microseconds) electromagnetic transients, through electromechanical power swings (milliseconds), to slower modes influenced by the prime mover boiler and fuel feed systems (seconds to minutes) [2]. Traditional power system modeling and simulation techniques can be classified into two main groups: a) Electromagnetic Transient (EMT) simulations and b) Fundamental Frequency (FF) simulations. While EMT simulations focus on fast phenomena with small time constants, FF simulations cover slower phenomena such as electromechanical oscillations [3].

Although EMT tools represent the most accurate modeling approach available for power systems [4], the high complexity of realistic-size power systems with thousands of busses have led to simplified stability studies in order to obtain the dynamic response of the system within acceptable computational time and resources [4]. In these simplified studies, also known as Transient Stability (TS) studies, the focus is on slow electromechanical transients, typical in conventional synchronous generators (SGs), while fast electromagnetic phenomena related to the network and other fast-response devices are neglected. These simplifications have been justified so far mainly due to the following reasons:

- In conventional power systems dominated by SGs, fast electromagnetic transients decay rapidly compared to the relevant time constants for system stability. As a consequence, there is little justification for modelling their effects in stability studies [5].
- The high complexity of real power systems had made impossible to perform stability studies based on detailed dynamic models of system components due to the computational burden required to solve the set of differential-algebraic equations.

Although simplified stability studies have had worldwide acceptance during the last decades, the increased use of converter-based variable generation technologies (VGTs) such as variable speed wind turbines and photovoltaic generation has led to question the validity of such studies. With increasing incorporation of VGTs, the dynamic response of the power system starts to be progressively more dependent on (complex) fast-response power electronic devices. Accordingly, the fast phenomena of power converters should start to dominate the dynamic behavior of the system thus changing the relevant time constants for system stability from electromechanical to electromagnetic time scale. In particular, the assumption that fast transients do not affect system stability may be incorrect in case of power systems dominated by VGTs [6]. This would invalidate traditional TS assessments, at least in power systems with high levels of VGTs.

This paper presents a first attempt to verify the of validity range of traditional TS studies in power systems with high levels of VGTs. To do this, first, a detailed modal analysis is carried out to understand the evolution of the system's modes as VGTs increases. Then, FF and detailed EMT simulations are performed considering different penetration levels of VGTs. Simulations are done in the IEEE 9-bus system using DIgSILENT Power Factory.

The next section presents the main characteristics of Fundamental Frequency (FF) and EMT simulations. Section III summarizes the main differences between the models used in both simulations. In Section IV the case study is presented. Finally, the obtained results are presented in Section V and the conclusions in Section VI.

II. Fundamental Frequency and EMT Simulations

Traditional power system modeling and simulation techniques can be classified into two main groups [7]: a) Electromagnetic Transient (EMT) simulations and b) Fundamental Frequency (FF) simulations also known as RMS (Root Mean Square), quasi-sinusoidal, or phasor-mode simulations. While EMT simulations focus on fast phenomena with small time constants (from milliseconds to hundreds of milliseconds), FF simulations covers slower phenomena such as electromechanical oscillations; ranging from hundreds of milliseconds to hundreds of seconds [7].

A. FF simulations

TS studies based on FF simulations compute the dynamic response of the system assuming a single-phase fundamental frequency behavior typically based on a positive-sequence representation [3],[7]. These studies use relative long time-steps in the order of 1 to 20 milliseconds [2]. This kind of simulations assumes that voltages and currents waveforms remain more or less at the fundamental frequency of the system (60 or 50 Hz) [3]. As a consequence, the electrical part of the network can be modelled considering steady-state voltage and current phasors. Therefore, distortions of the FF wave such as aperiodic components or harmonics cannot be taken into account [6]. The simplifications used in FF simulations allow solving the set of differential-algebraic equations of realistic-size power systems within acceptable computational resources and time [3].

Transient stability assessments play a key role in planning, operation, control, and stability studies of power systems [9].

B. Electromagnetic transient simulations

An alternative to FF simulations are EMT simulations. EMT tools represent the most accurate modelling approach available for power systems and especially for power electronic devices [2], [15]. EMT simulations cover a wide range of frequencies and use a time-step in the range of microseconds or less [3]. Electromagnetic transients are usually studied on a three-phase basis [8].

Detailed EMT simulations play an important role in design of protection schemes, insulation coordination, and design of power electronic converters [3],[15], in which cases single-phase FF simulations may fail.

C. Comments regarding VGTs

Compare to EMT simulations, TS studies based on FF simulations are much faster and suitable for stability assessments of large-scale (real) power systems. However, these studies use relatively long integration time-steps. Consequently, non-linear elements such as power converters are only represented by modified (average) steady-state models [2], meaning that fast phenomena like switching cannot be adequately represented. Since these devices are not represented in detail, the overall accuracy of traditional FF studies may be compromised, at least in case of power systems with high levels of VGTs. An accurate simulation of the dynamic response of fast-switching power electronic devices requires the use of very small time-steps to solve system equations.

III. Dynamic Models Used in FF and EMT Simulations

A. Conventional synchronous generators (SGs)

The classical approach to model SGs in TS studies based on FF simulations consists on transforming the physical variables into quadrature and direct magnetic rotor axis, which is known as the $dq0$ model [10]. There are various wide-accepted types of approximated models that uses the $dq0$ transformation [11],[12]: the sixth-order machine model, which is the highest model including the field circuit and three damper circuits in the dq coordinates; the fifth-order model, which includes two rotor circuits on the d-axis and one damper circuit on the q-axis; the fourth-order model which includes only the rotor circuit on the d-axis and one rotor circuit on the q-axis; the third-order model, which contains only the field circuit dynamics on the d-axis. All aforementioned models neglect stator transients and consider two differential equations for the mechanical coupling. Hence, stator quantities contain only FF components, and stator voltage equations appear as algebraic equations. This allows the use of steady state relationships for representing the transmission network and to focus the study in slow electromechanical transients.

For EMT simulations, stator transients are included in the model of SGs. Thus, the equations describing the behavior of stator variables are differential equations. Accordingly, the transmission network must be described by differential equations allowing representing the fast transients produced in the network and their interactions.

B. Transmission lines

FF simulations use steady-state relationships for representing the transmission network so that the study focuses on slow electromechanical transients of SGs [5]. Such steady-state relationship determines the voltage at an extreme of a line as [8]: $V = j\omega LI$ (losses are not included), where $j = \sqrt{-1}$ is the complex operator, ω the nominal frequency of operation, L the total inductance of the line, and I the current flowing through the line.

On the other hand, detailed line models used in EMT simulations computes the instantaneous evolution of the voltage and the current throughout a line. With this purpose, partial differential equations are used. This model of transmission lines is known as distributed parameter model. Equations (1) and (2) determines the evolution of the current and the voltage in a single phase of a line [8].

$$-\frac{\partial V(x,t)}{\partial x} = R' i(x,t) + L' \frac{\partial i(x,t)}{\partial t} \quad (1)$$

$$-\frac{\partial i(x,t)}{\partial x} = C' \frac{\partial V(x,t)}{\partial t} \quad (2)$$

where R', L', and C' are the resistance, inductance, and capacitance of the line that changes spatially, and x and t are the spatial and temporal variables. Equations determining how R', L', and C' change as a function of x are not included since very often constant parameters are considered or equivalently short lines are assumed.

A simplification often used in EMT simulations is to use the well-known π model with lumped parameters. In this case, equations (1) and (2) are simplified to:

$$-V(t) = Ri(t) + L\frac{di(t)}{dt} \tag{3}$$

$$-i(t) = C\frac{dV(t)}{dt} \tag{4}$$

C. Converter-based VGTs

In the literature several models have been reported to represent the behavior of converter-based VGTs. These models range from controllable voltage/current sources (that guarantee a determined power supply) to models that include some representation of the switching involved in the operation of the converters (mainly R_{on}/R_{off} or L_s/C_s models [13]). In FF simulations, simplified controlled voltage/current source models are used to represent the behavior of the converters. By contrast, in EMT simulations, the behavior of the power converters is usually modeled including the switching devices (either assuming that the devices are ideal switches or through resistances/inductances) [14]. However, the switching representation increases the complexity and computational burden of the model.

An alternative to include the fast dynamics of VGTs without highly increasing the complexity of the equations is to use an average model of the converter [15]. In this model, only the switching is neglected but the dynamics of the controllers and the phase-looked-loop (PLL) are included. The average model is described by the following equations:

$$\frac{d\vartheta}{dt} = k_{p\_pll}V_q + k_{i\_pll}\psi_{pll} \tag{5}$$

$$\frac{d\psi_{pll}}{dt} = V_q \tag{6}$$

$$\frac{de_{cd}}{dt} = i_d^* - i_{od} \tag{7}$$

$$\frac{de_{cq}}{dt} = i_q^* - i_{oq} \tag{8}$$

$$V_d = k_p\left(i_d^* - i_{od}\right) + k_i e_{cd} - \omega L_f i_{oq} \tag{9}$$

$$V_q = k_p\left(i_q^* - i_{oq}\right) + k_i e_{cq} + \omega L_f i_{od} \tag{10}$$

where ϑ is the phase angle of the voltage estimated by the PLL, V_q is the quadrature component of the voltage measured at the terminals of the converter, i_d^* and i_q^* are the reference values of the current in direct and quadrature axis, i_{od} and i_{oq} are the direct and quadrature components of the current injected by the converter at the connection point, e_{cd} and e_{cq} are the direct and quadrature components of the error signal of the current controller of the converter, k_{p_pll} and k_{i_pll} are the proportional and integral constants of the PLL, k_p and k_i are the proportional and integral constants of the current controller of the converter, and ω and L_f are the operation frequency of the converter and the inductance of the output filter.

IV. Case study

A. System under study

The study is carried out in the IEEE 9-bus system shown in Fig. 1 [4]. The system consists of three SGs, two of them with steam turbines (G2 and G3) and the last one with a hydraulic one (G1). The main characteristics of these generators are summarized in Table 1. The parameters of the lines and transformers can be found in [4]. The operating point under study considers a load of $315\ [MW]$ with 0.94 lagging power factor.

A wind turbine generator (WTG) is also connected to bus 4. The WTG is a variable-speed full converter type [16],[17] of $247\ MVA$ of rated capacity. The role of this WTG is to replace the hydro turbine and thus moving the network towards an inertia-less power system. Further details about the scenarios under study are given in Section V.

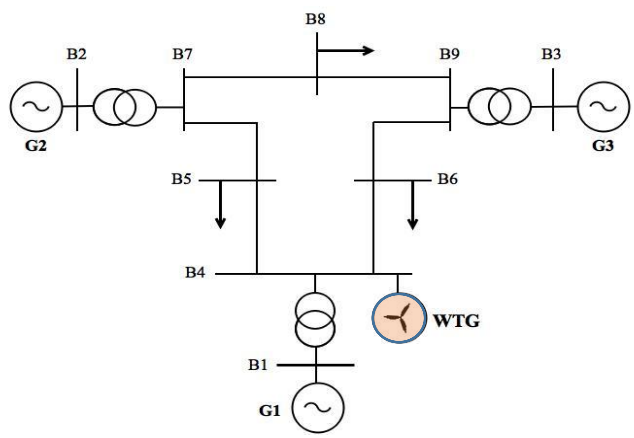

Fig. 1. IEEE 9-bus system.

Table 1. Characteristics of the SGs

Properties	G1	G2	G3
Type	Hydro	Steam	Steam
Rated power [MVA]	247.5	192	128
Inertia constant [s]	11.82	3.2	1.505
Rated voltage [kV]	16.5	18	13.8

B. Models and software used

The IEEE 9-bus system was implemented in the simulation tool DIgSILENT PowerFactory [18]. DIgSILENT support both, FF and EMT simulations. The main difference between these simulations is that EMT models considers both, transients of stator flux generator and transients of the transmission network. These phenomena are neglected in FF simulations. Thus, SGs are modelled with a sixth-order model in the FF simulations and with an eighth-order model in the EMT simulations.

The model of the SGs considers a standard automatic voltage regulator (AVR) type DC1A IEEE [17]. The speed regulator for the steam turbines is of type IEEE TGOV1 while the governor of the hydraulic turbine is the IEEE HYGOV [17].

The model of the WTG includes voltage regulation capacity during normal operation and fault ride through (FRT) capability during short circuits according to the grid code [19]. In this grid code, the reactive power support during contingencies is activated once the terminal voltage of the WTG leaves the deadband of ± 10 % around its steady state value. Frequency response capability is not considered in this study. The dynamic model of the converters is an average type, meaning that the switching is neglected for both, FF and EMT simulations as described in [16].

The model used for transmission lines is the π circuit model with lumped parameters in both, FF and EMT simulations. Finally, the load is modelled as a constant impedance for both kind of simulations.

V. Results

In this section we present the obtained results considering the system shown in Fig.1 for four scenarios:

- Base scenario: does not consider the WGT in bus 4.
- Scenario 10%: The WGT covers 10% of the total active load of the system.
- Scenario 35%: The hydro generator connected at bus 4 (G1) is fully replaced by the WGT. The WGT covers 35% of the total active load of the system.
- Scenario 70%: the WGT covers 70% of the total active load of the system.

Details about the generation dispatch in the considered scenarios are presented in Table 2.

Table 2. Dispatch of the SGs and the WTG per scenario

Scenario	Base	10%	35%	70%
G1	77		131	22
G2	80		80	80
G3	163		0	0
WTG	0		110	220
Percentage of system demand covered by WTG	0	10	35	70

As can be seen from Table 2, the injected power by the WTG is progressively incremented in the system starting from 0 MW (in the base scenario) until 220 MW in scenario 70%. It is important to highlight that when the WTG covers 35% and 70% of system demand, the hydraulic generator (G3) is no longer connected to the network.

A. Modal analysis

In this section we present the results of the modal analysis. The main objective is to understand the evolution of the system's modes as VGTs increases.

Figure 2 shows the eingenvalues of the system in the base scenario, i.e. without VGTs. It can be seen that the mode related to the faster phenomenon has a time constant of $\tau = 5\,ms$. Based on the participation factors, this mode is strongly related to the AVRs of the SGs. The rest of the eigenvalues have time constants ranging from $20\,ms$ to $3\,sec$. Furthermore, the frequency oscillations of the system modes are between 0.6 and $3\,Hz$.

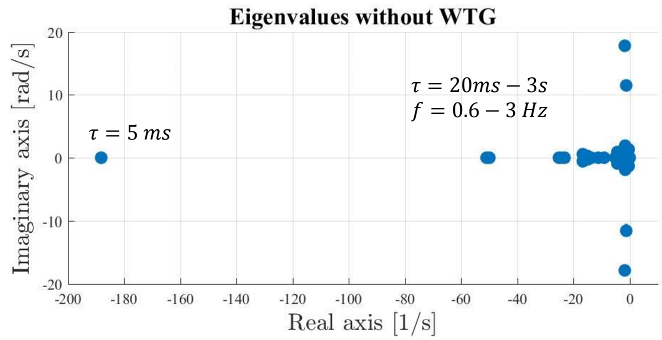

Fig. 2. Eigenvalues of the system in the base scenario

Fig. 3 shows the eigenvalues of the system considering different levels of VGTs. It can be seen that as the penetration of VGT growths, some "*fast oscillation modes*" start to appear in the system (left side of Fig. 3). In this work, "*fast oscillation mode*" is defined as a mode related to fast phenomena with a small time constants τ. These fast modes are related to the current control loop of the converters. Their time constants are around $2\,ms$, regardless the level of VGT. However, the oscillation frequencies differ depending on the scenario: the higher the penetration level of VGT, the higher the oscillation frequency. For instance, in scenario 10%, the frequency of the fastest mode is $8\,Hz$ and in the scenario 70% is $20\,Hz$.

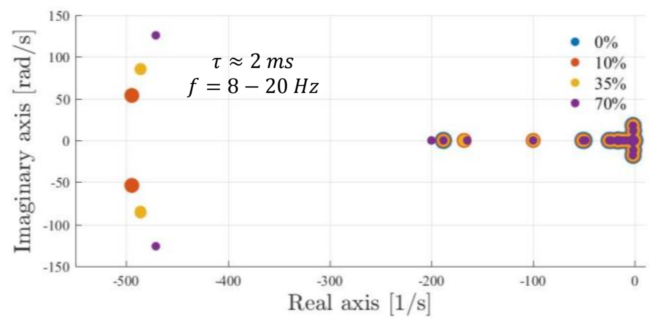

Fig. 3. Evolution of the eigenvalues as the level of VGT increases

B. Simulation results obtained in the base scenario

In this section, FF and detailed EMT simulations are performed in the base scenario, i.e. without VGTs. The considered contingency is a three-phase short circuit at the transmission line $B6 - B9$ applied at $t = 24\,sec$. The short circuit is cleared 150 ms after the fault appliance by disconnecting the faulted circuit.

Fig. 4 shows the speed of the generator G2 and the voltage at bus 6 using FF and EMT simulations.

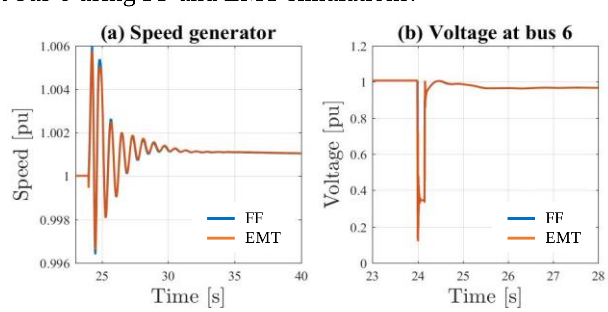

Fig. 4. FF and EMT simulation for base scenario. (a) Speed of generator G2, (b) Voltage at bus 6.

In steady state (once the fault is cleared), both simulations shows that the voltage at bus 6 and the speed of G2 reach the same final values of $0.967\ p.u.$ and $1.001\ p.u.$ respectively. By this way, when the WTG is not considered, it can be stated that the results obtained from FF and EMT simulations are exactly the same.

C. Results obtained considering 35% of penetration of VGT

Fig. 5 shows the speed of the generator G2 and the voltage at bus 6 for the same contingency as before (a three-phase short circuit at the transmission line $B6 - B9$). Fig. 6 displays the active and reactive power injected by the WTG.

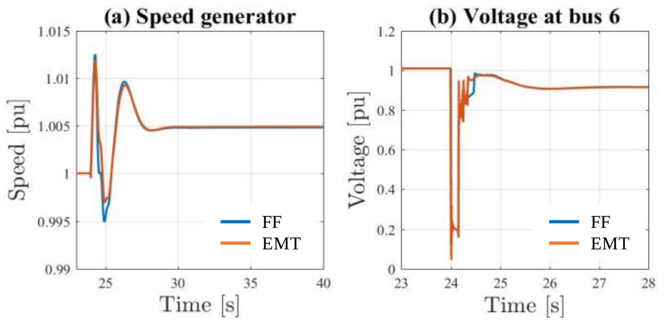

Fig. 5. FF and EMT simulation for scenario 35%. (a) Speed of generator G2, (b) Voltage at bus 6.

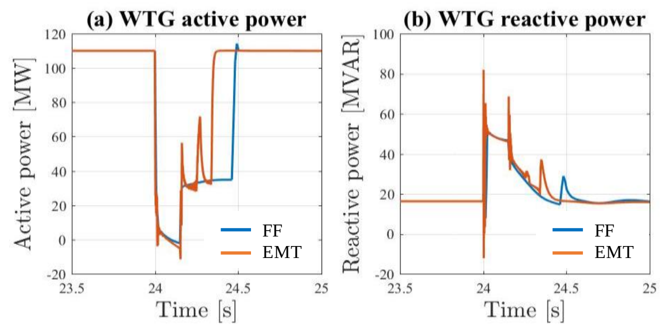

Fig. 6. FF and EMT simulation for scenario 35%. (a) WTG active power, (b) WTG reactive power.

From Fig. 5 it can be seen that the system reaches the same operating point in steady state regardless the type of simulation used. The voltage at bus 6 converges to $0.913\ p.u.$ after the fault clearance and the speed of G2 to $1.005\ p.u.$

Regarding the behavior of the WTG during the fault (Fig. 6), although larger oscillations are observed in the case of the EMT simulation, once the fault is cleared, both simulations reach the same steady state values for the active and reactive power injected by the WTG. Moreover, Fig. 6 also shows that the FRT control of the WTG is correctly activated during the voltage dip by injecting reactive power to support voltage stability.

Since no significant differences are observed in the dynamic response of the system, it is concluded that for this penetration level of VGT (35%), traditional TS studies based on FF simulations gives good results from a stability perspective.

D. Simulation results obtained in scenario 70%

Fig. 7 displays the terminal voltage of the WTG for the same contingency. The dashed lines represent the bandwidth considered in the voltage control to define the "*normal operation mode*". Fig. 8 displays the active and reactive power injected by the WTG.

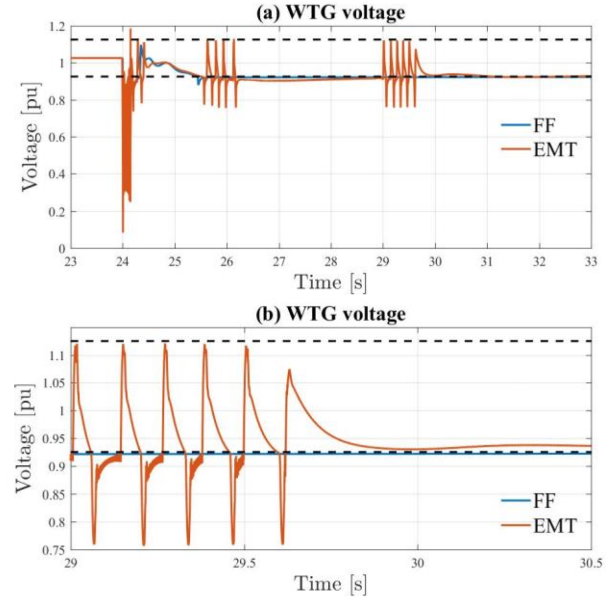

Fig. 7. (a) Voltage at the terminals of the WTG for scenario 70%, (b) Zoom of the voltage.

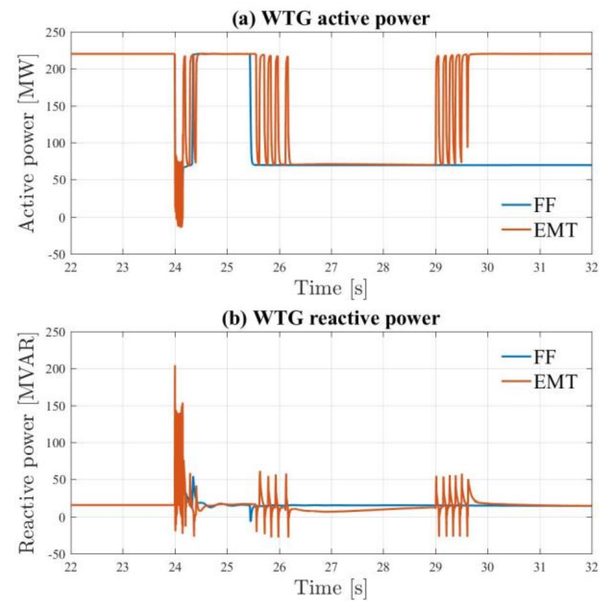

Fig. 8. FF and EMT simulation for scenario 70%. (a) WTG active power (b) WTG reactive power.

Fig. 7 shows that the voltage evolution in both simulations differ significantly. In the case of the EMT simulation, once the fault has been cleared, the voltage exhibits some noticeable oscillations around its lower limit for normal operation. When this happen, the WTG changes constantly from "*normal operation mode*" to "*fault mode*", thus significantly changing the obtained results. On the other hand, in the case of the FF simulation, the final value of the voltage after the fault clearance is in the region of "*fault mode*". Although the voltage value is slightly below its lower limit, the "*fault mode*" is sustained during the whole simulation. Accordingly, the active power injected by the WTG decreases significantly. This can be confirmed in Fig. 8 (a). This operation of the WTG has a direct effect on the system frequency stability.

Based on the simulations, it can be said that when the converter-based VGTs supply 70% of the system demand, the results obtained with FF simulations may significantly differ from those achieved through detailed EMT simulations thus confirming the increased importance of modelling fast phenomena as VGTs increases.

VI. Conclusions

This paper has presented a first attempt to verify the validity range of traditional transient stability (TS) studies based on fundamental frequency (FF) simulations in power systems with high levels of converter-based variable generation technologies (VGTs). The study was carried out in the IEEE 9-bus system.

The modal analysis showed that as the penetration of VGT growths, some oscillation modes related to fast phenomena of the converters start to appear in the power system. Their time constants are around $2\,ms$ regardless the level of VGT. However, the oscillation frequencies of these modes differ depending on the scenario: the higher the penetration level of VGT, the higher the frequency. These fast modes are not present in the base scenario without VGTs.

Regarding the dynamic assessment, the obtained results have shown that for low penetration levels of converted-based VGTs (less than 35%), TS studies based on FF simulations deliver similar results to those obtained through detailed EMT simulations. However, for higher levels of VGTs (70%), FF simulations provide different conclusions to those obtained when a detailed modelling of the system components is carried out (EMT simulations). By this way, as power systems move towards systems dominated by converter-based generation technologies, fast phenomena related to different network components start to play an important role in the dynamic behavior of the system. Accordingly, the assumption that fast transients do not affect system stability may be incorrect.

These *first results* may invalidate traditional TS assessments under high levels of converted-based VGTs. However, further studies are needed in order to set definite conclusions. In particular, it is important to characterize the evolution of the relevant time constants for system stability as a function of the penetration level of VGTs. By this way, it will be possible to define upon which point fast phenomena related to power converters must be considered for stability assessment purposes.

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