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Transient Overvoltages Simulation Due to the Integration Process of Large Wind and Photovoltaic Farms With Utility Grids

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ABSTRACT Integration of the renewable energy sources with utility grids is receiving more impressive concerns to provide extra-green energy sources to work in parallel or to phase out the sources with fossil fuels. The effects of the transient surges are the most vital parameters that are used in the insulation coordination studies for integrated systems of smart grid. Therefore, the electromagnetic transient overvoltages caused by switching surges and faults on the smart grids are the competitive design issues. Moreover, the contingency analysis of either sources or loads patching/dispatching is one of the major issues in the design process of the power system grid. The transient overvoltages imposed over the integrated grid systems need to be more properly investigated using most sophisticated numerical methods. Although, the transient surges have relatively short durations, but it may cause severe overvoltages stresses for the insulation systems and consequently may yield to insulation failure. This paper presents the simulation of large-scale renewable energy resources integrating with the utility grid. The transient overvoltages appear over the utility grids due to different renewable energy resources are investigated. Moreover, the different methods that proposed to be used to suppress, mitigate, and control these overvoltages and to minimize their probable sever effects over the permissible insulation level (BIL) are elaborated. Furthermore, the full simulation of the IEEE 39 grid integrated with large Photovoltaic and wind farms using EMTP-RV /MATLAB is developed. In addition, different proposed methods to mitigate and to control internal surges are investigated. Finally, the obtained results are presented with very good consistency level and compliance with other research studies found in literature and with the different standards related to the renewable energy sources.

INDEX TERMS Transient overvoltages in power grids, large-scale renewable energy sources, integration with power grids, mitigation techniques.

I. INTRODUCTION

Recently, renewable energy sources are initiated with imperative demand in many countries worldwide. These sources are working either in isolated networks or connected to utility grids. The term of Smart Grid (SG) is nominated to a class of technology that uses computer-based remote control and automation. The smart grid provides magnificent chance for electric power systems upgrading by the utilization of sustainable energy sources such as solar systems with Photovoltaic (PV) or wind turbine (WT) [1], [2]. Nevertheless, the smart grids (SG) are subjected to different overvoltages established due to different external/internal surges. Many studies tackled the effects of the external source such as the direct and indirect lightning strokes on the solar Photovoltaic (PV) and wind farms [3]–[6]. Meanwhile, many studies were interested with the internal sources of overvoltage surges such as switching operations and fault conditions [7], [8]. The major sever problem of the Smart Grid (SG) is the weakness of the Photovoltaic (PV) and wind farms when exposed to the overvoltage surges that might be imposed from the distributed systems. Therefore, the voltages and frequencies generated from the photovoltaic and wind should be controlled properly when integrated with the grids [9], [10]. Intentionally, this controlling process is to minimize the surge perturbations that might cause grid instability. Moreover, the transient

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overvoltages are to be controlled or mitigated to increase the grid reliability and to reduce the probability of the insulation failure risk. The grids should be almost free from voltage sags, spikes, disturbances and interruptions [11], [12]. Yet, the integration process of the new green energy sources still needs more elaborated work to have optimum utility grids with proper integration. The guidelines for Extra High Voltages (EHV) networks may need to be adequately updated to present the influences of the integration process of the new renewable energy sources [13], [14]. Many researchers aim to study the integration process from the power flow or power quality point of view [15], [16]. During static performance of smart grids, the low value of X/R ratio of the line impedance will affect the accuracy of the load sharing by each inverter and will cause unbalances. Meanwhile, during the dynamic performance of the smart grid, the voltage and frequency dependencies on the load should be considered when dropping one or more source units to avoid fail of control that will lead to instability [17], [18]. Short-term of voltage stability is a phenomenon that could happen during the large penetration of large- scale of renewable energy resource and during many other transient perturbations. Some studies are addressing the issue of dynamic VAR for improving short-term voltage stability [19], [20]. Therefore, the short-term voltage stability is vital to the stability of power grids specially when integrating with large-scale renewable energy resources. Furthermore, the short-term voltage stability involves dynamics of fast acting load components such as induction motors, electronically controlled loads, and HVDC converters. Modern power systems are operating under more stressed situations due to the increasing load demands and electricity exchange between regions. Moreover, their dynamic responses are more complicated with the increasing use of induction motor loads (such as air-conditioners), electronically controlled loads, HVDCs and renewable power generations. As a result, the power systems are more vulnerable to short-term voltage instability. It is considered that part of the reason for the North American blackout in August 2003 may be related to SVS [21], [22]. To describe the short-term voltage stability SVS, it is required to define three indices. The first index is based on the transient energy function while the second index is based on critical clearing Time and the third index is based on the voltage signals [23]. The electromagnetic transient overvoltages during patching and dispatching of the renewable energy sources to the smart grids or due to internal sources are rarely tackled and need to be elaborated intensively with the proper methods for mitigations. Many countries have abundant lands with sunny weather and high wind speeds which can provide super locations for renewable energy sources. Some of these countries can be considered a sun-belt country with about 2,000 to 3,000 kWh/m2/year of direct solar radiation. The sun can shine 9-11 hours or more per day few cloudy days [24], [25]. The current research presents full simulation for the integration process of two different renewable energy sources with the IEEE 39 bus utility grid. The main contribution of the current research is standing clearly about how much of transient overvoltage will be imposed over the grid during the integration process. Moreover, it presents the different techniques for mitigating the effects of the integration process with large-scale renewable energy resources PVs and Winds farms. To be more precise and tunned with the main objectives, the current paper simulates and investigates the electromagnetic transient overvoltages due to patching large-scale solar (PV) and wind farms. In addition, the system performance under fault conditions is demonstrated. Moreover, this research presents the different methods that could be used to suppress, mitigate these transient overvoltages. The effects of the induced transient overvoltages over the insulation level are elaborated. The simulated system of the smart grid with PV and wind farms is developed using EMTP/MATLAB. The simulation results are verified and found to be consistent with the different studies in the literature.

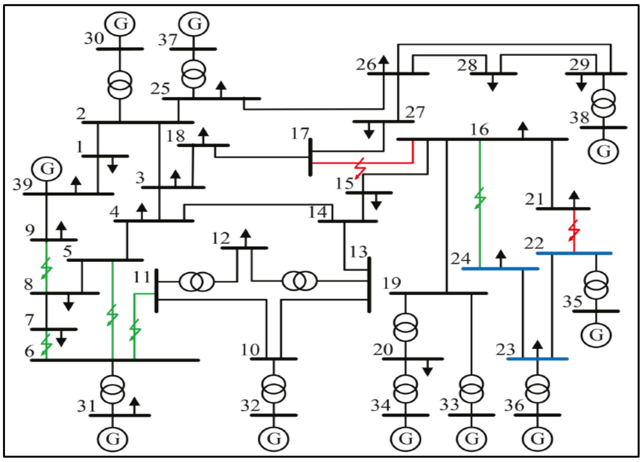


FIGURE 1. Single line diagram of the 39-bus transmission system.

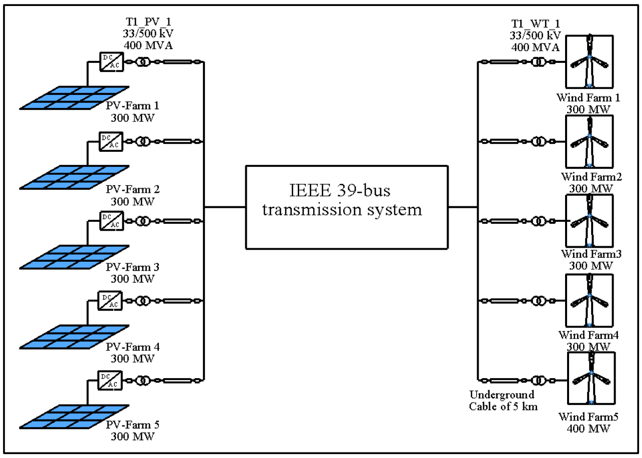


FIGURE 2. The simplified single line diagram of the simulated systems.

II. GRID SIMULATED SYSTEM

A. GRID DESCRIPTION

In this section of the current research, the grid system with two large-scale renewable energy sources PV and wind are simulated. The selected grid is IEEE 39-bus system that consists of loads, capacitor banks, transmission lines, and

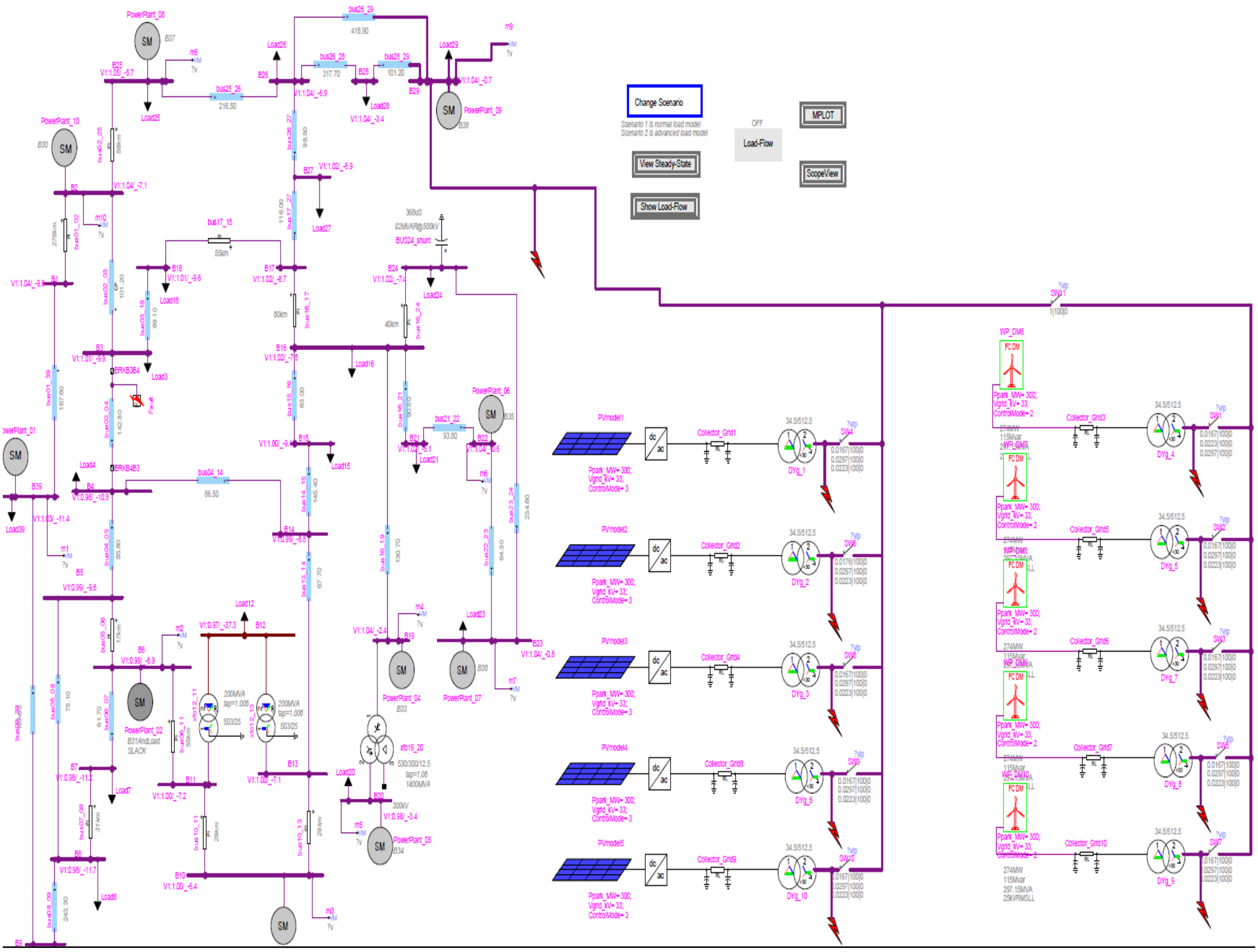


FIGURE 3. Screenshot of the simulated IEEE 39 bus system with PV and wind farms.

generators. This grid is 500 KV (RMS line-line) transmission system with 10 generators, 29 load buses and 46 transmission lines. Figure 1 presents the single line diagram of the 39-bus transmission system. Table 1 tabulates the main data of the grid and the simulated solar and wind farms. Figure 2 presents the simplified diagram of the simulated systems.

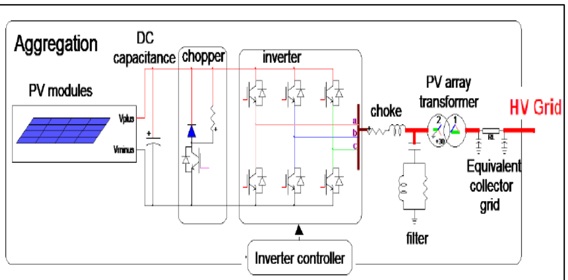
The solar PV system consists of 5 sub-farms and each farm is with 300 MW meanwhile, the wind system consists of 5 sub-farms and each farm is with 300 MW. Each PV and wind farms will be connected individually to the selected bus on the grid. Based on the load flow studies bus no 29 as in Figure 1 is selected to be the connecting point. Different scenarios for patching of the renewable sources will be tackled as shown in the screen shot of the simulated system in Figure 3. The main target is to investigate the different overvoltage surges developed during patching the new sources with the grid. Furthermore, the simulated system investigates the performance of the grid under normal and fault conditions. This simulation can be considered as a pre-design powerful tool for system designer and utility engineers to avoid any mal operation or power discontinuity problems.

TABLE 1. The main data of the simulated system.

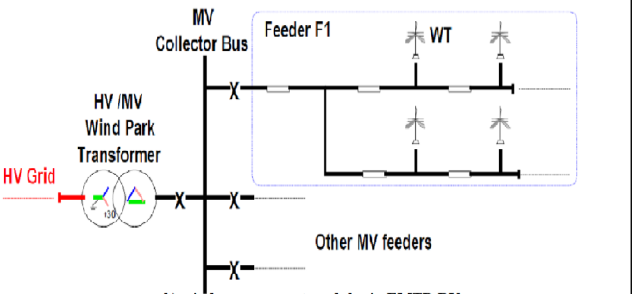
PV main parameter	Value
Total generated power (GW)	1.5
Grid nominal voltages (kVrms L-L)	500
DC voltage (kV)	1.264
Solar Irradiation (W/m2)	1000
Wind main parameters	
Total generated power (GW)	1.5
Grid nominal voltages (kVrms L-L)	500
DC voltage (kV)	1.15
Stator Generator Frequency (Hz)	60
The utility grid main parameters	
No. of buses	39
Grid nominal voltages (kVrms L-L)	500
No. of transmission lines	46
Sum of generator capacities GW)	7
Utility connected load (GW)	6
Grid frequency	60

B. REGULATION OF GRID INTEGRATION WITH RENEWABLE SOURCES

The basic grid requirements (grid codes) should be fulfilled to provide minor integration problem and to guarantee power



a) PV arrangement modules in EMTP-RV



b) wind arrangement modules in EMTP-RV

FIGURE 4. Screenshots of the PV and Wind system modules in EMTP.

quality of the grid systems. Different standards are developed to unify the general regulations for grid integration with renewable energy sources [26]–[29]. These standards are used to provide ancillary regulations that should be compromised for patching the PV and the wind systems with the utility grid. Generally, the total harmonic distortion for the grid voltage should not exceed 5% to avoid adverse effects on other equipment connected to the grid.

C. SIMULATION SOFTWARE PACKAGE

The IEEE 39 bus system is simulated using the EMTP-RV integrated with the MATLAB software package. The EMTP-RV is a powerful and super-fast computational engine that provides significantly improved solution methods for nonlinear models, control systems, and user-defined models. The engine features a plug-in model interface, allowing users to add their own models. EMTP-RV has the user-friendly and intuitive Graphical User Interface, provides top-level access to EMTP-RV simulation methods and models. It offers drag-and-drop convenience that lets users quickly design, modify and simulate electric power systems. It can be used for small systems or very large-scale systems. It can be integrated with MATLAB and moreover, it is integrated with ScopeView as Output Processor for Data display and analysis. ScopeView displays simulation waveforms in a variety of formats that helps users to dramatically reduce the time required to setup a study using EMTP-RV.

D. PVs AND WIND FARM MODELS USING EMTP-RV

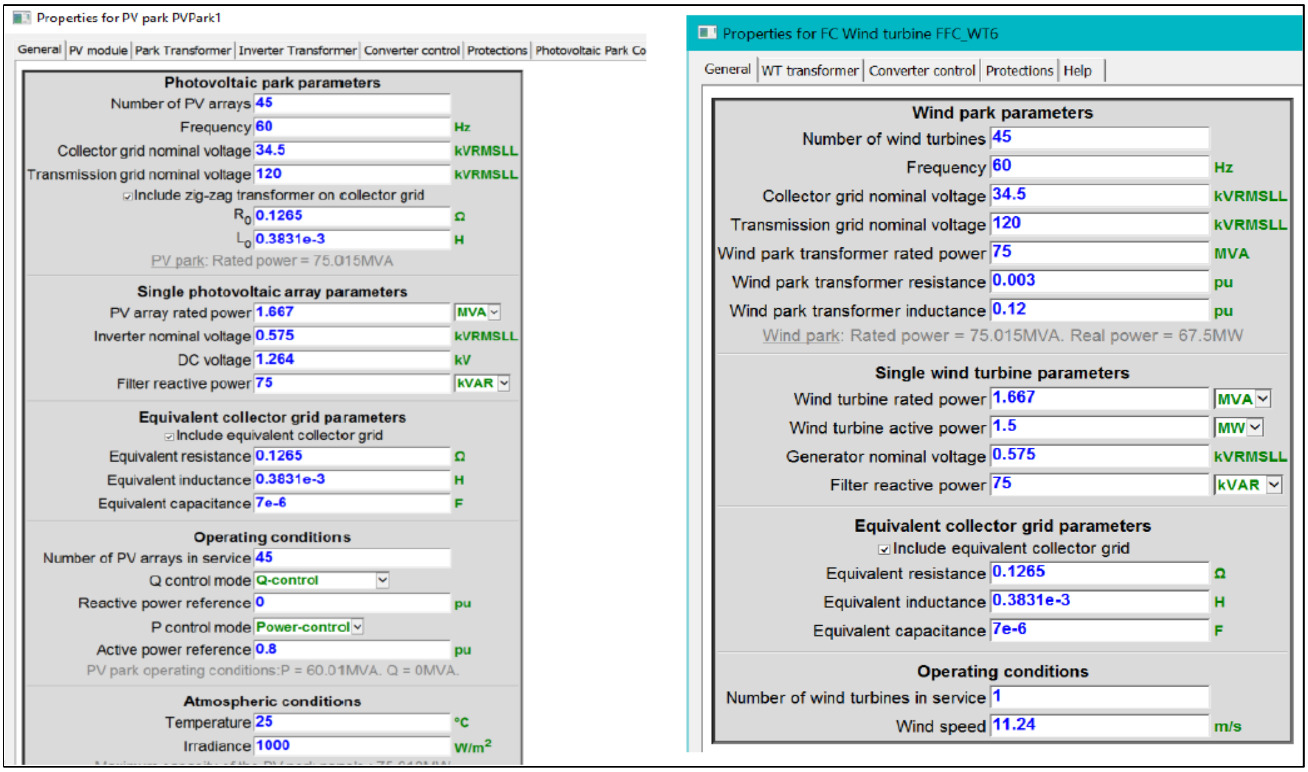
EMTP simulations provide good understanding of power system dynamics performance during normal and transient conditions [30]. EMTP presents models with simulation language makes it possible to simulate the different power system components. It is a symbolic and general-purpose description language. The model calculates the monitoring and controllability parameters of the power system as well as some other algebraic and relational operations for programming. The model has the capability to enable the user for describing the physical constants and/or the functional subsystems of the target systems. All the procedures and the main equations for the simulation of the PV and the wind systems are presented by [31]–[34]. Figure 4 presents the screenshots for the under-mask design general details for PV and wind systems with connecting to the grid with using EMTP-RV software package for simulation. The developed PV and wind system model's setup in EMTP are encapsulated using a subcircuit with a programmed mask as illustrated in Figure 5. The model interface consists of many tabs facilities to be used for adjusting the different design parameters of PV and wind systems.

The PV system model in EMTP consists of a solar panel, a Low/Medium PV array transformer, equivalent PI circuit of the collector grid and a MV/HV PV transformer. The different tabs of the PV mask allow the user to modify the general PV parameters (number of PV arrays in the PV park, power output and collector grid voltage levels). The general PV array parameters include PV array rated power, voltage, and frequency while the PV operating conditions include the number of PV arrays in service, operating mode and reactive power at grid connection and the atmospheric conditions. The other tabs are used to add and adjust the inverters and transformer main parameters in addition to many other design parameters. In addition, there is associated JavaScript file for tunning the PV parameters. The main interface of the PV model is shown in Figure 5. The wind system model in EMTP enables the user to modify the general wind system parameters (number of WTs in the WP, power output and collector grid voltage levels, collector grid equivalent transformer. The general wind turbine (WT) parameters include the rated power, voltage and frequency while the wind operating conditions include number of WTs in service, wind speed WPC operating mode and reactive power (or power factor) at grid connections. The associated JavaScript for wind plant (WP) Parameters can be used to compute the internal model parameters. It also contains the data that is not accessible from the mask, such as the data for WT aerodynamics, mechanical system and pitch control. The main interface of the PV model is shown in Figure 5.

III. SIMULATION RESULTS

A. GRID WITH AND WITHOUT CONNECTING PV AND WIND FARMS

Figure 6 and Figure 7 present the different overvoltages that appear on bus no. 29 for connecting different PV and wind farms with different capacities of 0,300,600,900,1200 and 1500 MW, respectively. This scale is proposed by the Electric holding company of Egypt for two different projects. It can be noted that, for PV penetration with 300 MW, the phase



Properties for PV park PVPark1

General | PV module | Park Transformer | Inverter Transformer | Converter control | Protections | Photovoltaic Park Co

Photovoltaic park parameters

Number of PV arrays 45
Frequency 60 Hz
Collector grid nominal voltage 34.5 kVRMSLL
Transmission grid nominal voltage 120 kVRMSLL
☑ Include zig-zag transformer on collector grid
R_0 0.1265 Ω
L_0 0.3831e-3 H
PV park: Rated power = 75.015MVA

Single photovoltaic array parameters

PV array rated power 1.667 MVA
Inverter nominal voltage 0.575 kVRMSLL
DC voltage 1.264 kV
Filter reactive power 75 kVAR

Equivalent collector grid parameters

☑ Include equivalent collector grid
Equivalent resistance 0.1265 Ω
Equivalent inductance 0.3831e-3 H
Equivalent capacitance 7e-6 F

Operating conditions

Number of PV arrays in service 45
Q control mode Q-control
Reactive power reference 0 pu
P control mode Power-control
Active power reference 0.8 pu
PV park operating conditions:P = 60.01MVA. Q = 0MVA.

Atmospheric conditions

Temperature 25 °C
Irradiance 1000 W/m²

Properties for FC Wind turbine FFC_WT6

General | WT transformer | Converter control | Protections | Help

Wind park parameters

Number of wind turbines 45
Frequency 60 Hz
Collector grid nominal voltage 34.5 kVRMSLL
Transmission grid nominal voltage 120 kVRMSLL
Wind park transformer rated power 75 MVA
Wind park transformer resistance 0.003 pu
Wind park transformer inductance 0.12 pu
Wind park: Rated power = 75.015MVA. Real power = 67.5MW

Single wind turbine parameters

Wind turbine rated power 1.667 MVA
Wind turbine active power 1.5 MW
Generator nominal voltage 0.575 kVRMSLL
Filter reactive power 75 kVAR

Equivalent collector grid parameters

☑ Include equivalent collector grid
Equivalent resistance 0.1265 Ω
Equivalent inductance 0.3831e-3 H
Equivalent capacitance 7e-6 F

Operating conditions

Number of wind turbines in service 1
Wind speed 11.24 m/s

FIGURE 5. Screenshot of the interfacing modules for defining the main parameters of the PV and wind.

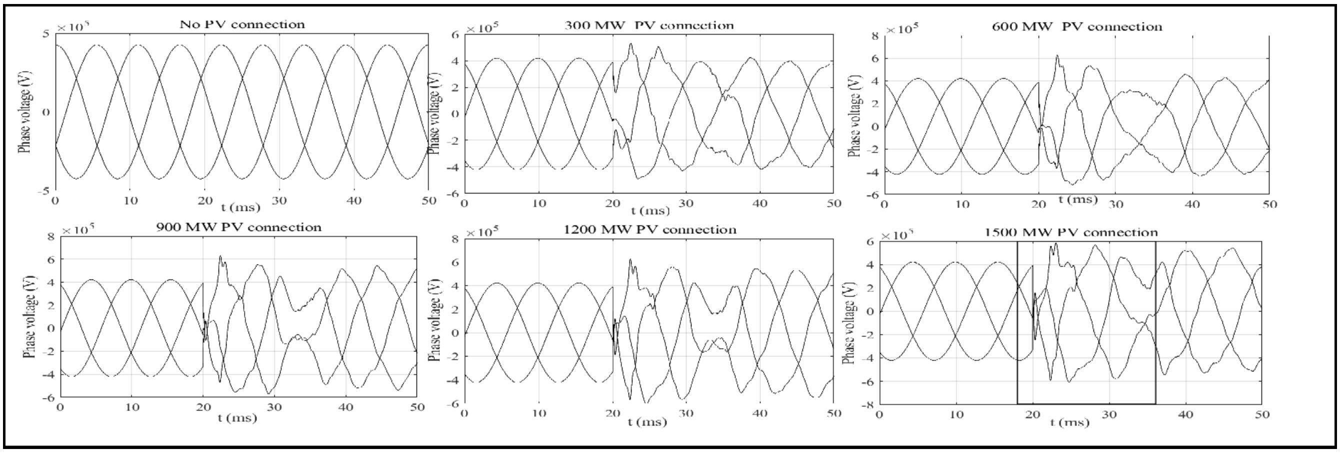


FIGURE 6. The phase voltage at bus no. 29 for the different PV capacities connection with the grid.

voltage is increased by about 20 % while with 1500 MW penetration it is increased by 48%. It can be noted that, for wind penetration with 300 MW, the phase voltage is increased by about 40 % while with 1500 MW penetration it is increased by 85%. For maximum penetration of 1500 MW of PV and wind, the total harmonic distortion is about 4.25% and 4.75%, respectively. The statistical values for the different scenarios are tabulated in Table 2. Figure 8 presents the phase voltages waveform of phase (A) under different penetration capacities of PV and wind, respectively. The total harmonic distortion for solar PV penetration spans a range between 4.06 to 4.25 meanwhile, it spans between 4.15 to 4.75 for wind (WT).

B. GRID UNDER FAULT CONDITION WITH MAXIMUM PENETRATION

The fault condition is simulated by allocating three – phase short circuit fault at bus no 29 with considering the maximum penetration of 1500 MW PV and wind farms. Figure 9 presents the phase voltages during fault with maximum penetration capacities of 1500 MW PV and wind on bus no. 29. It can be noted that for PV penetration there is lower wave distortion while with wind farm the wave of phase voltages is more distorted when connecting after the fault. This is due to the dynamic effects of the inertia of the wind turbine. Figure 10 presents the magnitudes and frequencies analysis

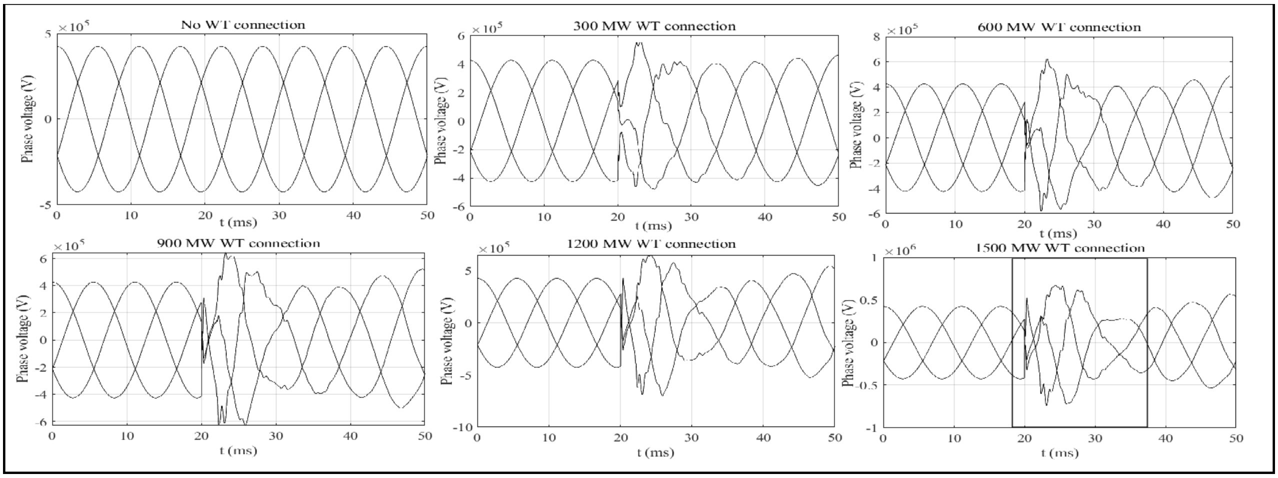


FIGURE 7. The phase voltage at bus no. 29 for the different WT capacities connection with the grid.

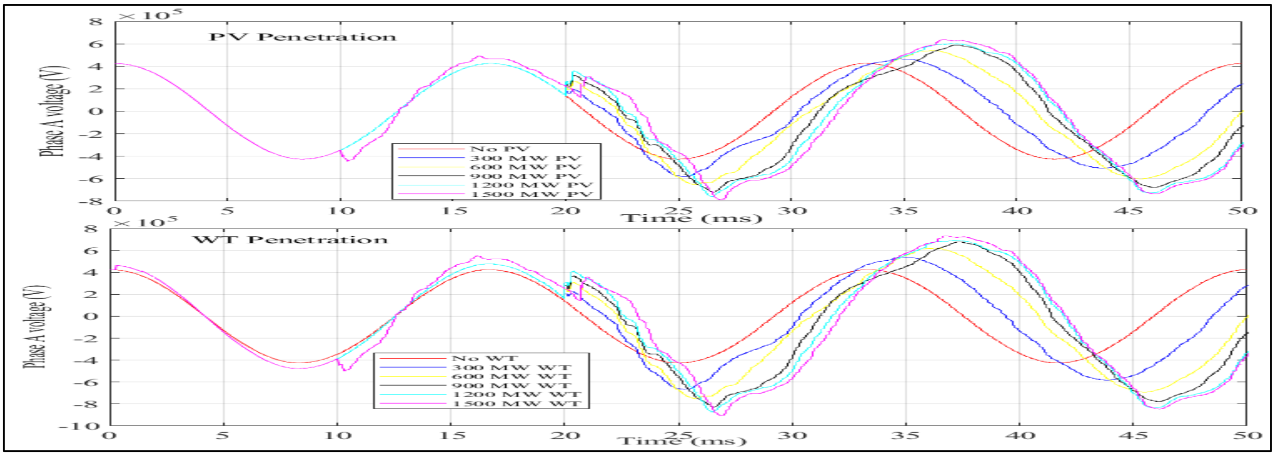


FIGURE 8. Phase (A) voltage waveform at bus no. 29 for the different PV and WT capacities connection with the grid.

TABLE 2. Statistical values for different penetration capacities of PV and WT.

PV penetration at bus No. 29					
Penetration capacity (MW)	Statistical values (KV) (Phase -A)				
	MIN	MAX	MEAN	STD	THD%
0	0.02	426	270.5	131.6	0
300	0.351	492	255.9	132.5	4.06
600	0.075	513	257.5	136.1	4.1
900	0.352	556	273.7	146.4	4.18
1200	0.358	600	279.8	145.7	4.23
1500	0.03	610	283.3	147.2	4.25

WT penetration at bus No. 29					
Penetration capacity (MW)	Statistical values (KV) (Phase -A)				
	MIN	MAX	MEAN	STD	THD%
0	0.02	426	270.5	131.6	0
300	0.113	579	296.5	148.4	4.15
600	0.114	653	325.6	169.5	4.2
900	0.115	720	352.2	181.9	4.21
1200	0.234	758	370.1	194.2	4.32
1500	0.094	765	382.7	197.5	4.75

to show how many times of equal values are repeated during the faults of PV and wind maximum penetration of 1500 MW.

From Figure 10, The voltages and frequencies relationship for faults with PV system is more normalized that the case with using the wind system. This is because of the dynamic effects of the wind turbine inertia.

IV. OVERVOLTAGES MITIGATION METHODS

Obviously, the maximum overvoltages obtained from the different scenarios are ultimately high and may cause serve problems for insulation failure and power continuity. Therefore, the overvoltages must be mitigated to minimize any prospective problems. There are many different overvoltage mitigation techniques such as using shunt reactors, surge arrestors, pre-insertion resistors and controlled switching of the circuit breakers [35]. The overvoltages mitigation techniques analyzed in this research are controlled switching of the circuit breakers and using shunt reactor. The penetration of 1500 MW will be considered for analysing the different effects of the mitigation techniques.

A. CONTROLLED SWITCHING

The controlled switching technique is based on closing each pole of the circuit breaker individually. This should be

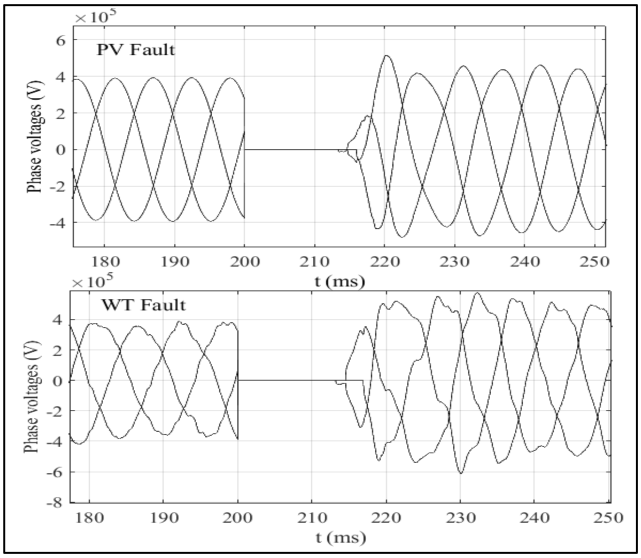


FIGURE 9. Phase voltages at bus no. 29 during three-phase short circuits for the different PV and WT with 1.5 GW.

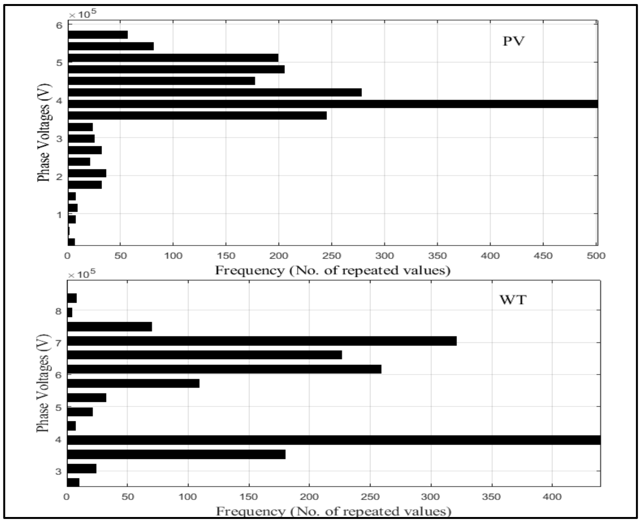


FIGURE 10. Phase voltages at bus no. 29 during three-phase short circuits for the different PV and WT with 1.5 GW.

executed at the optimal moment of each phase to minimize switching overvoltage (preferably with no loading or at starting). This is performed in a fashion that the switching of the circuit breaker poles is delayed occurring very close to the voltage across circuit breaker zero crossing point [35], [36]. For the simulated system with frequency of 60 Hz, the periodic time is (1/60) = 16.67 ms. The closing instants for phase A is equals 12.5ms, for phase C is 15.28ms and for phase B is 18.06 ms. The closing sequence starts by phase A at zero crossing followed by the phase C and then by phase B with delay of 60°. Figure 11 presents the phase voltages of PV and wind farms penetration of 1500 MW with using the controlled switched mitigation technique. For PV penetration, the maximum phase voltage is reduced by about 5% and the total harmonic distortion is reduced by about 12%. For wind penetration, the maximum phase voltage is reduced by about 6% and the total harmonic distortion is reduced by about 13%.

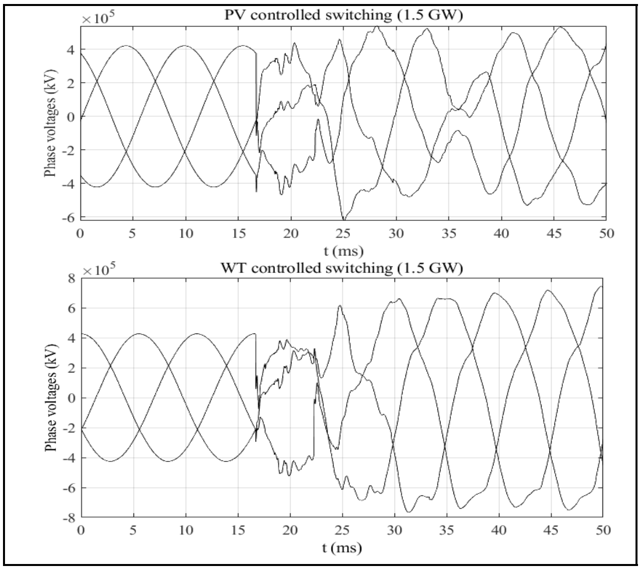


FIGURE 11. Phase voltages at bus no. 29 with controlled switching for the different PV and WT with 1.5 GW.

TABLE 3. Statistical values for different mitigation methods of PV and WT 1.5 GW penetration.

PV penetration at bus No. 29					
NO mitigation					
Penetration capacity	Statistical values (KV) (Phase -A)				
	MIN	MAX	MEAN	STD	THD%
1500 (MW)	0.03	610	283.3	147.2	4.25
Controlled switching					
Penetration capacity	Statistical values (KV) (Phase -A)				
	MIN	MAX	MEAN	STD	THD%
1500(MW)	0.02	575	262.5	142.5	3.75
Shunt capacitors					
Penetration capacity	Statistical values (KV) (Phase -A)				
	MIN	MAX	MEAN	STD	THD%
1500 (MW)	0.05	581	258.6	141.6	3.9
WT penetration at bus No. 29					
NO mitigation					
Penetration capacity	Statistical values (KV) (Phase -A)				
	MIN	MAX	MEAN	STD	THD%
1500 (MW)	0.094	765	382.7	197.5	4.75
Controlled switching					
Penetration capacity	Statistical values (KV) (Phase -A)				
	MIN	MAX	MEAN	STD	THD%
1500(MW)	0.01	720	381.5	201.5	4.14
Shunt capacitors					
Penetration capacity	Statistical values (KV) (Phase -A)				
	MIN	MAX	MEAN	STD	THD%
1500 (MW)	0.06	740	378.7	202.6	4.35

B. SHUNT REACTORS

Shunt reactor of 400 MVAR is allocated at bus no 29 with maximum PV and wind penetration of 1500 MW to monitor and to investigate its effects on the switching phase overvoltages. Table 3 tabulates the statistical values of the switching overvoltages at bus no. 29 of PV and wind penetration of 1500 MW with allocating shunt reactors of 400 MVAR. For PV penetration with 1500 MW and 400 MVAR shunt reactor, the maximum phase voltages are reduced by about 8 % while the total harmonic distortion is reduced by 5 %. For wind penetration with 1500 MW and 400 MVAR shunt reactor, the maximum phase voltages are reduced by about 4 % while the total harmonic distortion is reduced by 8 %. Most of the results found in literature showed that that the transient overvoltage imposed to the grid with integration with renewable energy resources is with 40% and it remains for about 1 and half cycle [37-40] The obtained results are compared with other research works and standards. The obtained results are with reasonable consistency with the other works and standards.

V. CONCLUSION

The switching overvoltages for integrating large-scale renewable energy sources PV and wind are simulated using EMTP/MATLAB software packages. The integration process is simulated using IEEE 39 bus grid with two renewable energy sources of different capacities ranged from 300 MW to 1500 MW. The effects of different penetration capacities are demonstrated. Nevertheless, the mitigation techniques of controlled switching of the circuit breakers and shunt reactors are investigated to minimize the switching of PV and wind sources. Moreover, the statistical analysis of mitigation methods applied to the simulated system is elaborated. The switching overvoltages due to integration process of 1500 MW PV and wind are higher than their base values by 48% and 85%, respectively. The mitigation techniques can reduce the overvoltages due to PV and wind integration by about 6% and 8% respectively. Based on the obtained results for the controlled switching method, the controlled switching technique is recommended. This technique can effectively minimize the switching overvoltages for integrating PV and wind farms. The obtained results are compared with other studies found in literature and some standards with very good compliance.

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