MODELING AND SIMULATION OF HYBRID DISTRIBUTED GENERATION AND ITS IMPACT ON TRANSIENT STABILITY OF POWER SYSTEM

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Abstract: The present grid is accommodating mixed energies resulting into increasing complexities and instabilities. The dynamic performance is measured by also considering the impact the integration of new technologies such as distributed generation (DG) and hybrid distributed generation (HDG) have on the grid. Hybrid distributed generation with one or more renewable (stochastic) energy sources interact with the existing grid during import and export of power generation. This interaction contributes more fault current therefore making the system vulnerable to instability more than a single energy source. This study investigates the dynamic impact of hybrid Wind/ PV/small Hydro power on transient stability. To investigate this impact, a detail modeling of grid connected wind / solar PV and small hydropower system with single machine infinite system is carried out. The simulation was done in DIgSILENT power factory software. The configuration of the proposed typical grid connected hybrid distributed generation (HDG) consists of variable speed Wind turbine with doubly -fed induction generator (DFIG), solar PV and small hydropower system. The wind turbine is integrated through PWM converter into the existing Grid while the solar PV incorporated into the system consists of DC sources integrated through PWM inverter and the hydro power is directly connected through a synchronous generator.

Index Terms: Hybrid distributed generation, stability index, and critical clearing time. Wind turbine, Solar PV, Hydropower system, export, import, distributed generation

I. INTRODUCTION:

Distributed generation can be defined as a small capacity power plants based on either combustion based technologies, such as reciprocating engines and turbines, or non-combustion based technologies such as fuel cells, photovoltaic, wind turbines, etc[1]. These are located near the end–users and are characterized as renewable or co-generation sources [1]. Currently, there is wide-spread use of distributed generation across the globe though the level of penetration is still low [2]. By year 2020, the penetration level of DG in some countries such as USA is expected to increase by 25% as more independent power producers; consumers and utility company imbibe the idea of distributed generation [3]. However, the rapid progress in renewable energy power generation technologies, and the awareness of environmental protection have been the major reasons why alternative energy and distributed generation is a promising areas [4]. Because some of renewable energy sources can complement each other, multi-source alternative energy systems have great potential to provide higher quality and more reliable power to consumers than a system based on a single source [5]. The larger the penetration level of hybrid distributed generation (HDG) in a power system, the more difficult it becomes to predict, to model, to analyze and to control the behavior of such system [5]. Some HDG using induction generators are not grid friendly because they consume reactive power instead of generating it. Most power converters do not have adequate control mechanism to actively support DG integration. The system inertia for some of them (e.g., solar PV or fuel cell) is extremely low. They are weather dependent with constant daily load variation [6]. Also, existing protection mechanism might not be able to take care of the problem of bi-directional power flow that takes place due to DG connection in radial networks. New design controllers are needed to effectively manage the multi-energy sources distributed generation in other to service remote villages.

Due to the natural intermittent properties of wind and solar PV, stand alone wind/PV renewable energy systems normally require energy storage devices or some other generation sources to form a hybrid system. In an electrical power grid without energy storage, energy sources that rely on energy stored within fuels (coal, oil, gas) must be scaled up and down to match the rise and fall of energy production from intermittent energy sources. In this way the operators can actively adapt energy production to energy consumption in other to increase efficiency and lower the cost of energy production and to facilitate the use of intermittent energy sources. In the USA the demand for electricity generation is mainly driven by price volatility i.e using distributed generation for continuous use or for peaking use (peak shaving) [3]. During seasonal changes, some energy sources might have to switch on during off peak hour while other during peak hour in other to reduce cost and enhance load balancing within the system. These configurations among many other things need to be investigated to know the dynamic interaction between the hybrids distributed generation and the grid.

Several works have been done on distributed generation but most of the works are based on single energy source [5, 6,7,8 and 9]. Ref [10] investigated the impact of high penetration of DG on transient stability. The DGs considered in the case study are synchronous and asynchronous generators. It is found that DG influences the system transient stability differently depending on DG penetration levels, DG grid- connection-strength, different DG technologies, and DG protection schemes of converter-connected. Reference [4] modeled and examined the dynamic impact of fuel cell on transient stability of power system network. Reference [11] investigated the impact of high penetration of Solar PV on the transient stability. Several other papers reported the dynamic state of the system as the penetration level increases. Also several hybrid power systems have been developed [12-13]. An isolated network for very low voltage decentralized energy production and storage based on photovoltaic and wind was developed, mainly considering the energy management and control of the photovoltaic and wind hybrid system [14]. A grid connected hybrid scheme for residential power supply based on an integrated PV array and a wind-driven induction generator were discussed [15, 16].

However, all the hybrid power systems were based on steady state, unit sizing, optimization techniques in other to extract maximum power from the hybrid system and standalone. None of them mention transient state and none either consider additional energy sources such as small hydropower system. Interaction of HDG interaction, additional power transmitted across distribution corridor, unexpected fault, bidirectional power flow form Hybrid DG, electromechanical oscillation due to system with different inertia constant, torsional interaction of wind turbine with power system control and grid are some of the new things to investigate for effective integration of HDG in other to prevent the future grid from any unexpected cascaded event that can lead to serious technical challenges. This study investigates the dynamic impact of hybrid Wind/ PV/small Hydro power on transient stability. To investigate this impact, the modeling of grid connected wind /Solar PV/small hydro power with single machine infinite system were carried out in DIgSILENT power factory. The configuration of the proposed typical grid connected hybrid distributed generation (HDG) consists of variable speed Wind turbine with doubly-fed induction generator (DFIG), Solar PV and small hydro power. The wind turbine is integrated through PWM converter into the existing grid while the solar PV incorporated into the system consists of DC sources integrated through PWM inverter. The small hydropower system is modeled as synchronous generator.

The rest of the paper is organized as follows: Section II summarizes distributed generation concept while section III describes the hybrid distributed generation. Section IV gives the mathematical modeling of HDG. Section V describes the simulation setup in DIgSILENT. Section VI gives the transient stability indicator and section VII gives the results and discussion. Conclusion is described in section VIII.

II. DISTRIBUTED GENERATION CONCEPT.

Small generators connected to the distributed network in other to service the consumer load is called distributed generation. However, a large wind farm connected to the network to meet consumer demand is also assumed to be distributed generation. Presently, the promising sources of distributed generation are wind turbine and Solar PV. A PV cell harvest energy directly from sunlight and converting it to electricity. Due to the high cost, they were initially preferred only for space research applications. Later, as the cost of PV began to decrease, several other applications were developed. Attempt to decrease the cost has brought the use of organic semiconductors like conjugated polymers [17] in the fabrication of solar cells. However, the running cost and the maintenance cost of these PVs as well as the long life usage make it an attractive alternative energy source. The drawbacks are:

1) The variability of the energy sources causes instability to the grid.
2) Consumers that are supplied by PV are likely to be in blackout in the night as PV does not supply energy during the nights.
3). Lack of inertia constant contributes to the poor voltage regulation and low power quality produce by PV array. It therefore increases instability during fault. Also, wind turbine especially the doubly-fed induction generator has the ability to provide supplementary active and reactive power to the existing grid.

It converts energy inherent in wind to electricity through wind turbine, shaft, induction generator and various controllers to ensure proper grid integration and friendliness. Like PV, wind output power depends on the availability of wind. The variability of energy sources is a concern as it is a hot area of research over decade ago. It is clean and renewable and environmentally friendly but is not reliable.
For some reasons, solar PV and wind turbine can form a viable hybrid power sources. Other energy sources that can form hybrid sources with solar PV are diesel generator, batteries, fuel cells, small hydropower system. [17]. Detail of the list can be found in ref [17]. A virtual remote village is considered to be practically visible for the implementation of the scheme. In other word, the location of wind and solar is site dependent and can be implemented basically in the following three modes of operation:

i) Import mode: The grid supplies additional active and reactive power to supplement the power generated by the hybrid DG ($P_{DG<} P_{CG}$) Note: $P_{CG}= P_{load}$

ii) Export mode: Excess power is exported to the grid. ($P_{DG}>P_{CG}$).

iii) Load =generation mode: The hybrid DG generates power that is enough to meet the load demand($P_{DG}=P_{CG}$) Where P_{DG} is the power generated by DG and P_{CG} is the power from the grid. The penetration level is defined as

$$\% PL_{DG}= \frac{P_{DG}}{P_{DG+P_{CG}}} \times 100 \qquad (1)$$

$\%PL_{DG}$ is the percentage penetration of the DG or hybrid DG. While P_{DG} is the power generated by two or more DG and P_{CG} is the power generated by the grid.

III. HYBRID DISTRIBUTED GENERATION CONCEPT

Many of the primary energy sources are complimentary and abundant in nature which gives it a good opportunity to increase availability, power quality and flexibility of power supply when they are fully optimized. The objective of the integration is to capitalize on the strengths of both conventional and renewable energy sources, both cogeneration and non-cogeneration types. However, Hybrid distributed generation system can be defined as a small set of co-operating units generating electricity and heat, with diversified primary energy carriers(Renewable and non-renewable), while the coordination of their operation takes place by utilization of advanced power electronics and are located closed to the consumers end.[17]. They are either grid connected or standalone system, renewable or nonrenewable system. The combination of hybrid power generation was represented in matrix form in ref [17]. Fig 1 shows the detail configuration of the proposed hybrid distributed generation. The import mode is shown in Fig1 and it describes how the load is supplied by the centralized generator and distributed generator. The export mode indicates that the HDG exported its excess generation to the grid. In the load= generation mode, the combination of the DG and GEN2 are used to supply the load with zero contributed to or from the grid (GEN1). Due to limited space only the Import mode is shown. The export mode can be explained when the excess power is released to the grid. The load=generation mode means that nothing was release to the grid.

Proposed Hybrid Distributed Generation Configuration

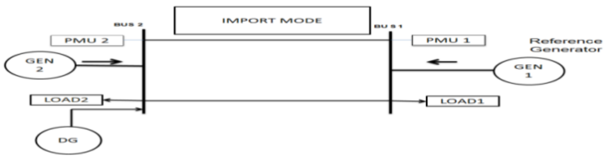

Fig 1: Configuration of the proposed hybrid distributed generation. (Import mode)

IV. Modeling of Hybrid distributed generation:

A. Modeling of wind Turbine

The variable speed wind turbine with DFIG consists of wind turbine, drive train, pitch controller, induction generator, rotor side converter and grid connected converter and grid model. The stator winding of the generator is coupled to the grid, and the rotor winding to power electronics converter, which today is usually back to back voltage source converter(VSC) with current loops. The mechanical and electrical rotor frequency is decoupled. This is achieved through the use of power electronics that offers compensation for the difference between mechanical and electrical by injecting a rotor current with a variable frequency. One of the main reasons for using DFIG today for wind generation is because it has the ability to control reactive power and to decouple both reactive power and active power control by independently control the rotor excitation current. The drawback is the need for slip ring. The range of variation of slips, determines the sizes of converters whose sizes are a fraction of the rated power. Though the grid side converter is not involved in reactive power generation yet the voltage is controlled by generating or absorbing reactive power from the grid. The system can been equipped with three controllers namely: speed controller, pitch angle controller and terminal voltage controller. The speed controllers adjust the generator torque in accordance with speed control characteristic. During high wind speed, controlling the generator torque by speed controller will lead to overloading the rotor converter and the generator. To solve this problem, pitch angle controller is activated. It works only when the pitch angle cannot control the speed any more as in high wind speed.

B. *Rotor equations modeling*

The general relations between wind speed and aerodynamic torque holds [18]:

$$T_t = \frac{1}{2}\rho\pi R^3 v^2 \frac{C_p(\lambda,\beta)}{\lambda} \tag{2}$$

And the power is shown as

$$P_w = \frac{\rho}{2} C_p(\boldsymbol{\lambda},\beta) A_R v_w^3 \tag{3}$$

The power coefficient C_p of the wind turbine in equation 2 is a function of tip-speed ratio λ which is given by:

$$\lambda = \frac{\omega R}{v} \tag{4}$$

Tt=turbine aerodynamic torque (Nm), ρ= specific density of air (kg/m3), v= wind speed (m/s), R=radius of the turbine blade (m), CP= coefficient of power conversion, β = pitch angle, P=power extracted from the airflow (W), $\boldsymbol{\lambda}$= Tip speed ratio,

ω= is the rotational speed of the wind turbine shaft

C. *Machine equations*:

Using the generator convention, the following equations are used in DFIG modeling.

$$v_{ds} = -R_s i_{ds} - \omega_s \varphi_{qs} + \frac{d\varphi_{ds}}{dt} \tag{5}$$

$$v_{qs} = -R_s i_{qs} + \omega_s \varphi_{ds} + \frac{d\varphi_{qs}}{dt} \tag{6}$$

$$v_{dr} = -R_r i_{dr} - s\omega_s \varphi_{qr} + \frac{d\varphi_{dr}}{dt} \tag{7}$$

$$v_{qs} = -R_r i_{qr} + s\omega_s \varphi_{dr} + \frac{d\varphi_{qr}}{dt} \tag{8}$$

d and q indicate the direct and quadrature axis component and s and r indicates the stator and rotor quantities. Where v is the voltage (V), R the resistance (Ω), I the current (A), ω the stator electrical frequency (rad/s), ψ the flux linkage (Vs) and s is the rotor slip.

The real and reactive power at the rotor and the stator can be calculated by

$$P_s = u_{ds} i_{ds} + u_{qs} i_{qs} \tag{9}$$

$$Q_s = u_{qs} i_{ds} - u_{ds} i_{qs} \tag{10}$$

$$P_r = (u_{dr} r + u_{qr} i_{qr}) \tag{11}$$

$$Q_r = (u_{qr} i_{dr} - u_{dr} i_{qr}) \tag{12}$$

For DFIG

$$P = P_s + P_r = u_{ds} i_{ds} + u_{qs} i_{qs} + u_{dr} i_{dr} + u_{qr} i_{qr} \tag{13}$$

$$Q = Q_s + Q_r = u_{qs} i_{ds} - u_{ds} i_{qs} + u_{qr} i_{dr} - u_{dr} i_{dr} \tag{14}$$

The value of Q fed into the grid in equation 14 above depends on the control of the power electronic in the grid sides .This does not affect active power except that the efficiency of the inverter can be incorporated into the last two variables. In this paper, for transient stability studies of power systems the wound rotor induction generator is represented by third order model as indicated in Dig SILENT [18]. In this case the model is obtained by neglecting the stator transients for the fifth order model of induction machine. It shows that there are three electrical equations and one mechanical equation. The model is in d-q expressed in rotor reference frame. In rotor reference frame, the d axis in the rotor reference frame is chosen collinear to the rotor phase winding and the position of the rotor reference frame is the actual position of the rotor.

The dynamic model of the induction generator is completed by mechanical equation:

The electrical torque can be expressed by:

$$T_e = \psi_{qr} i_{dr} - \psi_{dr} i_{qr} \tag{15}$$

Obviously, there is a change in generator speed as a result of the difference in electrical and mechanical torque. This is expressed as:

$$\frac{d\omega}{dt} = \frac{1}{2H}(T_m - T_e) \tag{16}$$

Where H is the inertial constant(s) and this is specified in DIgSILENT as acceleration time constant in the induction generator type. Tm and Te is the mechanical and electrical torque respectively.

D. Modeling of Small Hydro Power (SHP)Turbine

The power available in water current is proportional to the product of head and flow rate.
The general formula for any hydro power is:

$$P_{hyd} = \rho\, gQH \tag{17}$$

Where: P is the mechanical power produced at the turbine shaft (Watts), ρ is the density of water (1000 kg/m^3), *g* is the acceleration due to gravity (9.81 m/s^2), Q is the water flow rate passing through the turbine (m^3/s), H is the effective pressure head of water across the turbine (m). The hydro-turbine converts the water pressure to mechanical shaft power, which further rotates the generator coupled on the same shaft. The relation between the mechanical and the hydraulic powers can be obtained by using hydraulic turbine efficiency η_h, as expressed by following equations:

$$P_n = \eta_h\, P_{hyd} \tag{18}$$

$$Q = Av$$

And the whole equation is derive from Bernoulli's theorem which state

$$\frac{v^2}{2g} + h + \frac{p}{\rho g} = \frac{P_{hyd}}{\rho g Q} \tag{19}$$

Where v is the water flow speed (m/s), A is the area of the cross section (m^2) p is the pressure of water (N/m^2).

E. Solar cell modeling

PV effect is a basic physical process through which solar energy is converted directly into electrical energy. It consists of many cells connected in series and parallel. The voltage and current output is a nonlinear relationship. It is essential therefore to track the power since the maximum power output of the PV array varies with solar radiation or load current. This is shown by Matlab simulation. The equivalent diagram of a solar cell is represented by one diode model as shown in Fig 2.

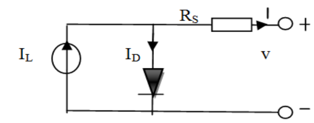

Fig 2: Model for single solar cell

The output terminal of the circuits is connected to the load. The output current source is the different between the photocurrent Iph and the normal diode current I_D. Ideally the relationship between the output voltage V and the load current I of a PV cell or a module can be expressed as [11,14,15,16].

$$I_{pv} = I_{ph} - I_D = I_{ph} - I_0[\exp\left(\frac{V_{pv}+iR_s}{mKT_c}\right) - 1] \tag{20}$$

Where I_{ph} is the photocurrent of the PV cell (in amperes), I_0 is the saturation current, Ipv is the load current (in amperes), Vpv is the PV output voltage(in volts), Rs is the series resistance of the PV cell (in ohms) and m, K and Tc represent respectively the diode quality constant, Boltzmann's constant and temperature.

The power output of a solar cell is given by

$$P_{pv} = V_{pv}\, I_{pv} \tag{21}$$

Where I_{pv} is the output current of solar cell (A). V_{pv} is the solar cell operating voltage (V), P_{pv} is the output power of solar cell (W). The output power depends on the temperature and the irradiance. The dependence of power generated by a PV array conditions can readily be seen in the current-voltage (P-V) and the power-voltage (1-V) characteristics of PV arrays.

V. SIMULATION SETUP IN DIgSILENT

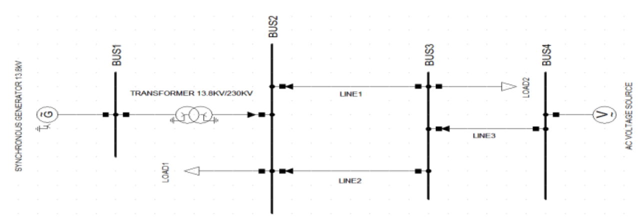

Fig3: Simulation Setup in DIgSILENT

The system is modeled in DIgSILENT power factory simulation tool as shown in (Fig3). The system model is a single machine infinite bus system with a synchronous generator modeled as PV rated at a capacity of 80MW and 40MVAR. This is connected to bus 2 via 100MVA transformer. The DG in this case is hybrid DG involving solar PV, wind turbine and small hydropower system. There are two loads each with 80MW and 40MVAR active and reactive power respectively. The grid is modeled as voltage source at 230kV. The transmission lines are model as RLC pi transmission lines. Line 1 and line 2 are 620km while line 3 is 310km. The DFIG is rated 8MW and 4MVAR, 0.85 power factor lagging. While the solar PV is modeled in DIgSILENT as dc current source with 8MW real power and zero reactive power. This is integrated to the grid by PWM inverter. The hydro power is model with 8MW real power and 4MVAR reactive power. A three phase short circuit fault was applied on line 2 at bus 2 at 4 seconds and cleared after 200ms by removing the line. The penetration level in the test system is varied in the following order.

(i) Import mode PL_{DG}=40% , (ii)Load =generation PL_{DG}=50%, (iii) Export mode PL_{DG}=120%

To combine these three DGs together an effective truth table was drawn considering Solar PV alone, , DFIG alone, SHP alone, SolarPV/DFIG, SolarPV/SHP/DFIG.

VI. Transient stability indicator

The commonest system stability index is the critical clearing times. The critical clearing time is the maximum allowable time to maintain synchronism. It measures the robustness of the system to various contingencies. If the fault is clear within this time, the power system remains stable. But if it is cleared after this time, the power system is most likely to loss synchronism. And the criterion for instability is when the first swing rotor angle exceed 120 degree otherwise it is stable. The setting of threshold is always based on power system characteristics. To assess the transient stability of every scenario, we apply a temporary 3-phase fault at line2 at different distance from bus 2. The location of the fault is 0%, 20%,40%,60%,80%,100% of the length of the transmission line. The CCT is obtained by increasing the fault duration until GEN 2 loses synchronism at 120degree.

VII. RESULTS AND DISCUSSIONS

The three scenarios considered in this paper are import, export and load =generation. The graph in Fig 4 shows the Rotor angle comparison between Solar PV-DFIG and hybrid Solar PV/DFIG (Import mode). It takes 38minutes for solar PV alone to reach steady state. The hybrid power takes lesser time to reach steady state as well as the DFIG. For solar PV, the rotor angle settle at -61.5^0 while the DFIG settles at -55.5^0 the hybrid one settle at -57^0. The hybrid power system shows an improvement because they are complimentary energy sources. The situation repeats itself for the other case also except in a case of hybrid DFIG/Solar PV /SHP system. The hybrid power system simulation in Fig7-9 shows an increasing rotor angle. The system is prone to instability if no adequate controller is provided. The case might also worsen if the numbers of generator increases. Instead of using three generators, if one decided to use four generators, the performance might be worsening resulting into instability. However, the impact of hybrid distributed generation depends on the technology, connection strength and the level of penetration.

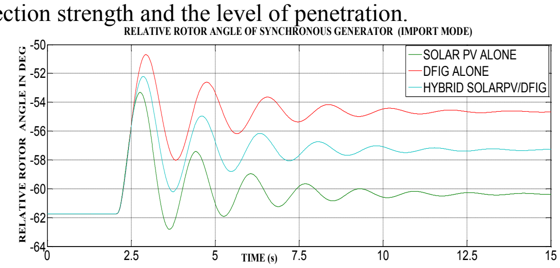

Fig 4: Rotor angle comparison between Solar PV,DFIG and Hybrid SOLAR PV/DFIG (Import mode)

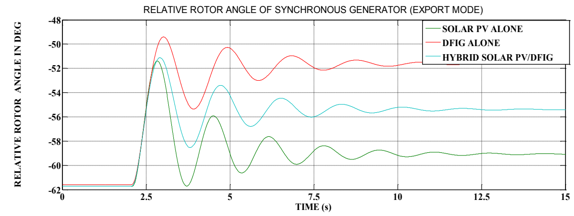

Fig 5: Rotor angle comparison between Solar PV-DFIG and hybrid Solar PV/DFIG (Export mode)

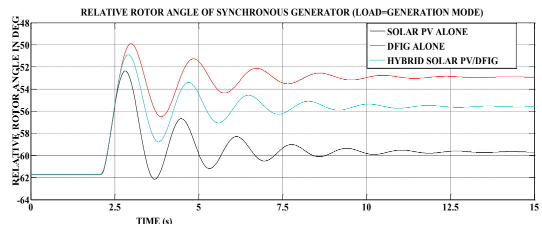

Fig 6: Rotor angle comparison between Solar PV,DFIG and Hybrid SOLAR PV/DFIG (Load=Generation mode)

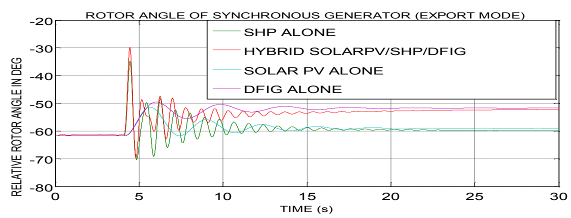

Fig 7: Rotor angle comparison between Solar PV-DFIG-SHP and Hybrid Solar PV/DFIG/SHP (Export mode)

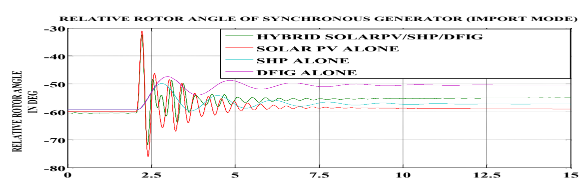

Fig 8: Rotor angle comparison between Solar PV-DFIG-SHP Hybrid Solar PV/DFIG/SHP (Import mode)

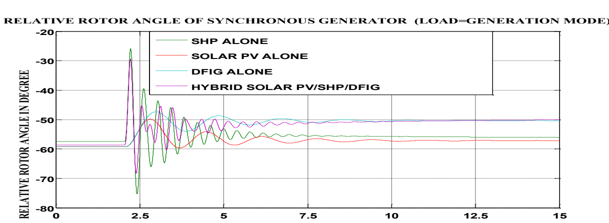

Fig9: Rotor angle comparison between Solar PV-DFIG-SHP and Hybrid Solar PV/DFIG/SHP (Load=Generation mode)

Table1: The critical clearing time of synchronous generator

with integrated Solar PV.

Fault location	Fault loaction	Import	Load=Generation	Export
In %	in km	CCT(ms)	CCT(ms)	CCT(ms)
0	0	340	335	330
20	124	440	430	420
40	248	540	520	500
60	372	600	570	550
80	436	560	530	500
100	620	430	430	400

Table2: The critical clearing time of synchronous generator With integrated Solar PV/SHP.

Fault location	Fault loaction	Import	Load=Generation	Export
In %	in km	CCT(ms)	CCT(ms)	CCT(ms)
0	0	350	430	340
20	124	480	440	430
40	248	640	600	590
60	372	800	730	690
80	436	770	700	670
100	620	560	530	510

Table3: The critical clearing time of synchronous generator with integrated Solar PV/DFIG.

Fault location	Fault loaction	Import	Load=Generation	Export
In %	in km	CCT(ms)	CCT(ms)	CCT(ms)
0	0	340	300	330
20	124	430	430	420
40	248	530	500	500
60	372	580	560	550
80	436	550	520	510
100	620	430	420	410

Table4: The critical clearing time of synchronous generator with integrated solar PV/DFIG/SHP

Fault location	Fault loaction	Import	Load=Generation	Export
In %	in km	CCT(ms)	CCT(ms)	CCT(ms)
0	0	340	330	320
20	124	470	420	400
40	248	630	510	480
60	372	790	550	510
80	436	750	520	480
100	620	550	410	390

Table1 shows the critical clearing time of integrating Solar PV alone. Comparing this with Table 2, 3 and 4 shows that the critical clearing time decreases with increasing penetration. Comparing the export mode of table 3 and table 4 shows that it is better to integrate two DGs than three DGs. For example at 0% distance the critical clearing time for export mode in table 3 is 330ms while 320ms at table 4. It shows that the fault can stay longer for Solar PV/DFIG than for Solar PV/ DFIG/SHP. The fault also can stay longer for Solar PV/SHP than for SolarPV/DFIG. At import mode the critical clearing time for the three DGs is better than for the two DGs but as the penetration begins to increase the CCT for the two DG (SolarPV /SHP) or (Solar PV/DFIG) is better.

VIII. Conclusion

Modeling and simulation of grid integrated Hybrid distributed generation is shown in this paper . It majorly investigates the impact of various complimentary energy sources on the power system network. The test system is single machine infinite system with integrated HDG. The system was observed by using oscillation duration and critical clearing time. The final report shows that, as the number of generator increases the stress on the system also increases. However, the simulation shows that hybrid power system with three generator show a critical cases compared to two DG. The result shows that the impact depend on the network strenght, level of penetration and the technologies involves.

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