Impact of Increased Penetration Levels of Distributed Inverter-based Generation on Transient Stability

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***Abstract* — The introduction of renewable energy (RE) generation onto the Grid has major benefits such as low carbon footprint on the environment and cheaper or free primary energy sources. However the introduction of RE generation is certainly not without challenges. One major challenge with introduction of non-synchronous RES on the Grid is erosion of natural inertial energy that is provided by synchronous machines on the Grid. This natural inertial response from synchronous generating sources helps in damping power system swings during system events such as generator trips or sudden loss of a large load. The primary benefit of system inertia in this manner is seen in primary frequency response of the power system, however inertial energy of the machine also directly affects the transient stability of the machine in question. It will be of interest to study how distributed non-synchronous generating sources impact on global transient stability in the power system. This paper will address the impact of increased penetration levels of distributed non-synchronous (static) RE generation on global transient stability of the power system.**

***Index Terms*—static generator, non-synchronous generator, inertia, transient stability, PV generation, Renewable generation, distributed generation.**

I. INTRODUCTION

The rapid increase in integration of renewable generation globally due to the drive to reduce carbon footprint on the environment, has led to concerns around the effect / impact on this integration on power system stability more especially when large fleets of static renewable generation displaces the conventional synchronous generation [3,4,5,6]. The main problem is that the inertia or stiffness offered by conventional generation will be largely eroded by the introduction of non-synchronous / static RE generation that interface to the power system via inverters leading to overall system stability[5]. Wind and Photo –Voltaic (PV) generation use inverters to integrate to the system; while PV is completely static with no moving parts, wind on the other hand does have a turbine that rotates but even this is normally asynchronous and is sometimes partly connected to the grid via a converter. But one strong factor of the integration of static renewable energy (RE) generation is the fact that it is distributed and closer to the load centres [6] and hence has a positive impact on reduction of losses which results in healthier receiving end voltages and improved power transfers.

PV and wind generation form the largest bulk of the RE roll-out around the globe. The study here will primarily focus on impact of distributed static (inverter-based) RE generation on transient stability of a power system. There are other stability concerns such as frequency stability and control due to erosion of inertial energy which will certainly affect primary frequency response and hence Ancillary services in this regard [5]. However, the scope of this paper will be limited to the impact on transient stability only.

II. THE SWING EQUATION

Transient stability is the ability of the power system to maintain synchronism following a severe disturbance such as a fault on transmission line, loss of generation, or loss of a large load [1].

Transient stability is dependent on the rotor angles of generators in a power system. It is dependent on all rotating mass in the power system including both generators and motors. However system operators, have more control over the generators. The motion of a generator's rotor is influenced by two forces namely; mechanical torque applied by the turbine (T_M), and the opposing electrical torque developed as a result of the electrical power output of the machine (T_E). The accelerating torque (T_A) on the rotor is the difference between T_M and T_E as per equation 1 below [2].

$$T_A = T_M - T_E \tag{1}$$

Where:

T_A is Rotor Accelerating Torque

T_M is Mechanical Torque Input

T_E is Electrical Torque Output

Because:

$$P \propto T \qquad (2)$$

Then,

$$P_A = P_M - P_E \qquad (3)$$

Where:

P_A is Rotor Accelerating Power

P_M is Mechanical Input Power

P_E is Electrical Output Power

The equation above is a power balance equation for the rotor. The mechanical power input to the rotor should come out as electrical power to the system. If there is a mismatch between mechanical power input and electrical power output then (P_A) rotor accelerating / decelerating power exists. When the mechanical power (P_M) input to the generator exceeds the electrical power output (P_E), the rotor will accelerate and hence store the excess energy. When the mechanical power input to the generator is less than electrical power output, the generator will decelerate by drawing the difference from its stored rotor energy [2].

III. POWER TRANSFER

The power transfer in MW between any two points is dependent on the torque or power angles. The torque angle is used when calculating the power transfer from a generator to the system. The power angle is used when calculating the power transfer between two locations in the transmission system. The same power transfer equation (equation 4) is used for calculations involving either power angle or torque angle [2]:

$$P_T = \frac{V_S V_R}{X} \sin \delta \qquad (4)$$

The following two figures show the impact of generator proximity to a load centre on power transfer and associated steady state stability:

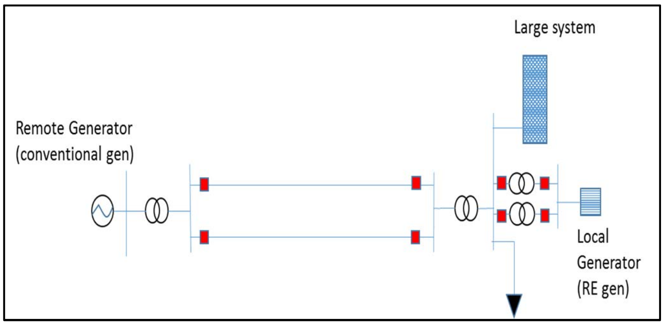

Figure 1: Proximity to load centre for a conventional generator and RE generator

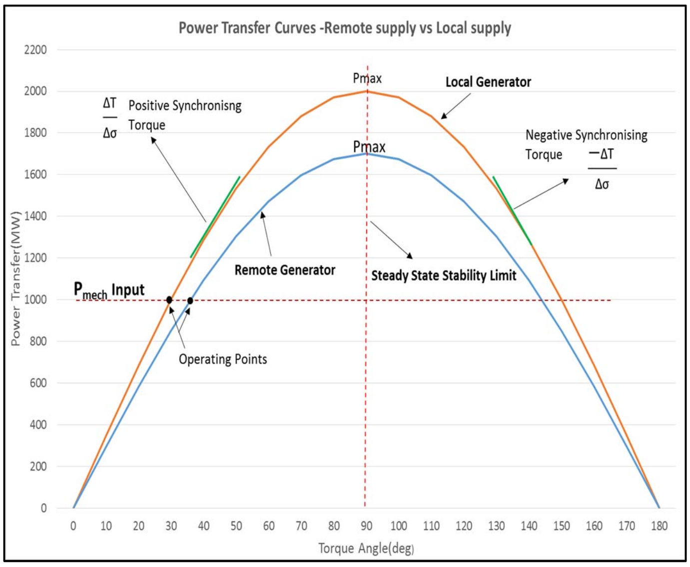

Figure 2: Power transfer curves for remote and local generator

Figure 1 shows that RE generator is usually connected very close to load centres as compared with traditional conventional units [3,6]. This proximity results in improved possible power transfers to the load centre as depicted in figure 2 above. Figure 2 shows that for the same torque (power) angle the RE generator transfers more power to the load than the remote conventional generator. This of course follows from equation 4 as the impedance (X) between the RE generator and the load is relatively reduced. Also for increasing mechanical input power, the RE generator electrical output margin before reaching steady state stability limit is relatively increased while the converse is true for the remote conventional generator.

IV. IMPACT OF GENERATOR PROXIMITY TO LOAD ON ITS TRANSIENT STABILITY

a) Local generation (i.e. RE generation)

The following figure 3 shows the previous system but now with a 3-phase fault on the HV side of the RE generator.

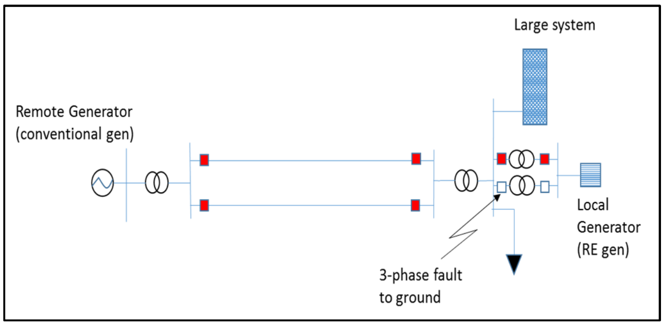

Figure 3: 3-phase fault to ground on the HV side of the RE generator

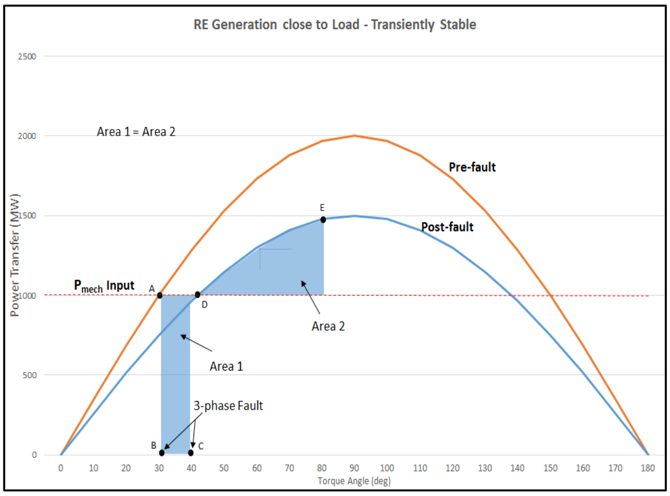

Figure 4:Power transfer curve assessing transient stability of a RE gen

Figure 4 shows assessment of transient stability of the RE generator after a 3-phase fault on the HV side of the RE generator. (note that the RE generator in this case; for illustrative purposes is not a static generator, but a synchronous machine).

The balanced 3-phase fault depresses the voltages on the generator terminal to zero and hence no power escapes the generator for the duration of the fault. The generator was operating at point A (with 1000 MW output), when the fault occurs the generator power drops to zero (point B) and the rotor angle accelerates (and stores the energy on the rotor) as the mechanical input power is greater than electrical output power. At point C the fault is cleared and the affected circuit tripped; the generator rotor angle jumps to the post fault curve (the impedance path has increased) and accelerates up to point D and after point D it decelerates as the mechanical input power is now less than electrical output power. The rotor continues to decelerate and expends the stored energy until it reaches point E where the accumulated stored energy is fully expended. The rotor now decelerates back to point D where it will oscillate back and forth about the point before settling there.

Area 1 which represents the energy the generator rotor angle accumulated during acceleration (stored energy) while Area 2 is deceleration energy which represents the usage of the stored electrical energy of the rotor. If area 1 is equal to area 2, then the generator is transiently stable. This is called equal area criterion. This is exactly the condition with the RE generator in the above case. The generator maintains stability post a 3-phase fault on its HV side.

b) Remote generation (i.e. Conventional generation)

The following figure 5 shows the system with a 3-phase fault on the HV side of the Remote conventional generator.

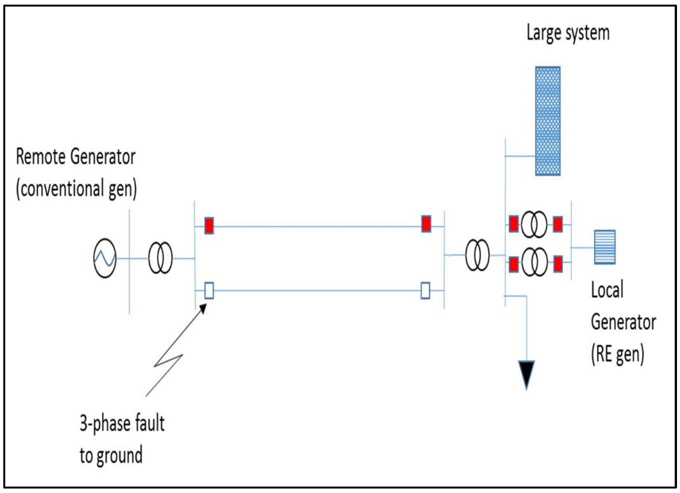

Figure 5: 3-phase fault to ground on the HV side of the Remote conventional generator

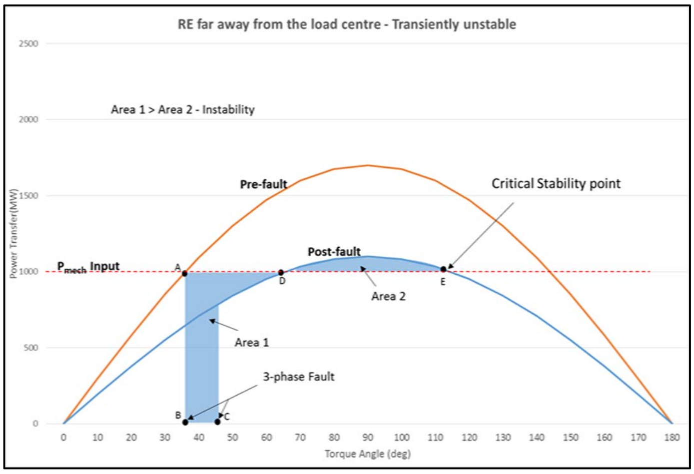

Figure 6: Power transfer curve assessing transient stability of a remote conventional gen

Figure 6 shows an assessment of the transient stability of a remote conventional generator after being subjected to a fault on its HV side. This generator like the RE generator is operating initially outputting 1000 MW (operating point A). A point of note here is that even the maximum power realizable in this case is only about 1700 MW while in the case of RE generation it was about 2000 MW. This is because of the increased impedance of the transfer path – two long transmission lines. A second point is that even though the remote conventional generator is outputting the same power as the previous local RE generation at point A, the rotor angle in this case is larger – about 35 degrees now compared to about 30 degrees previously – a larger torque angle presents a concern for stability.

A 3-phase fault occurs on the HV side of the generator, the rotor angle jumps to point B as the power and voltage depresses to zero. The rotor accelerates as the mechanical power input is higher than electrical power input. The fault is cleared at point C. (note that the same fault duration is still observed here as in the previous case). After fault clearing the rotor angle jumps to the post fault curve as the impedance is now higher since the faulted circuit has been tripped. The rotor continues to accelerate until point D and after point D it starts to decelerate as the mechanical power input now is less than the electrical power output. The rotor decelerates past 90 degrees as it has not fully expended the stored energy accumulated during acceleration. Beyond 90 degrees the synchronizing torque becomes negative and the rotor continues to decelerate until it reaches point E which is the critical stability limit, but by this point the stored energy in the rotor has still not been fully expended as the Area 2 is still less than Area 1. The rotor now accelerates after point E as the mechanical energy input is now greater than electrical energy output and stability is lost. It continues to accelerate until it reaches 180 degrees and past this point it will start motoring and accelerates even further. In a practical system by this point intervention by means of automatic tripping of the generator or using other protection techniques should have long happened as the accumulated stresses on the generator could lead to damage of the plant.

V. SIMULATION STUDIES TO TEST THE THEORY ABOVE

The study conducted here was done on a 39 bus New England System which is the simplified (reduced) model of the high voltage transmission system of New England. This is a test system that is widely by research organisations around the globe more especially for general dynamic behavior of the power system [3,4]. The results obtained from this test system in this study are generally expected not to be too far from other practical transmission systems around the globe and hence can be used to depict a general behavior of a transmission system [3]. The model with all parameters were taken from DigSilent Powerfactory examples. The system is a 6 GW system with 10 synchronous generators serving 19 load centres.

A. Methodology

RE generation in form of PV generation was placed on strategic buses; mainly load buses to depict a distributed generation as is the case with RE generation. A total of 8 load buses were connected with PV generation; namely: Buses: 39, 08, 04, 16, 03, 20, 15, and 24.

A base case scenario was developed with 0% RE penetration level. Then after PV generation was progressively increased from 20% up to 80% instantaneous penetration levels to depict different penetration scenarios. This was done in steps of 20% PV penetration. The conventional generation sources were thus proportionally curtailed to allow for additional RE generation.

Note: It was decided that the choice of whether PV or Wind was used did not matter much for the purpose of the study here since they both use inverter/converter system and thus would have the same impact on the network in this context.

The other scenario that was tested was a situation where RE generation is connected in such a way that it competes for the same power corridor with the conventional unit for evacuation of power. This was to check if this would not lead to transient stability problems on the conventional generator as the RE penetration levels increase thereby constraining the evacuation path in question.

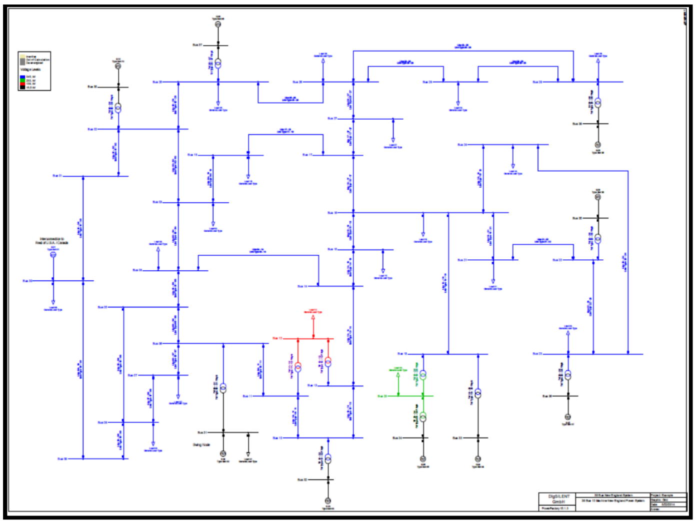

Figure 7: 39 Bus New England System

VI. TEST CASE 1: DISTRIBUTED RE GENERATION

For all the following scenarios, a 100ms fault was simulated at Bus 16 and was cleared by tripping the line 16 – 17. This contingency was observed to be a transiently stable contingency at a base case level after a contingency sweep of the entire system. Most contingencies resulted with transient instability in the base case and hence were not good cases to start from.

Base Case:

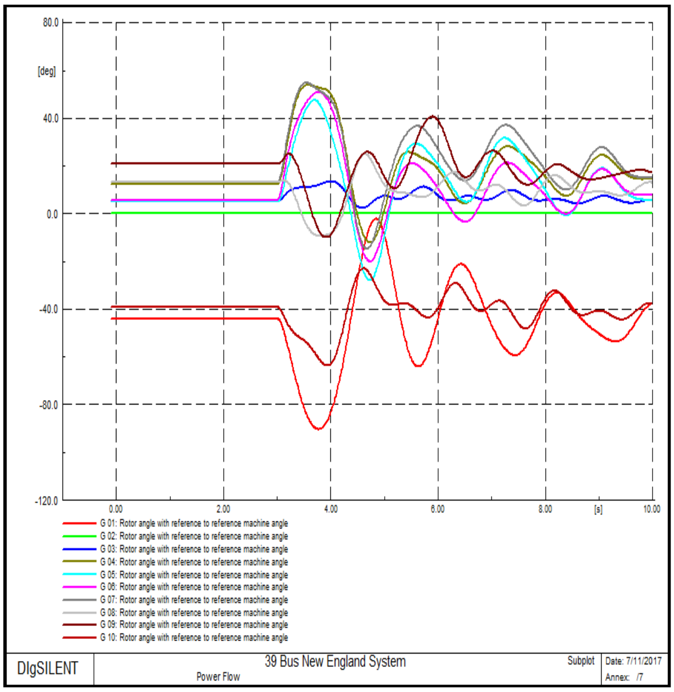

Figure 8: Rotor Angles of all 10 generators in the system with No RE

20% RE Penetration level:

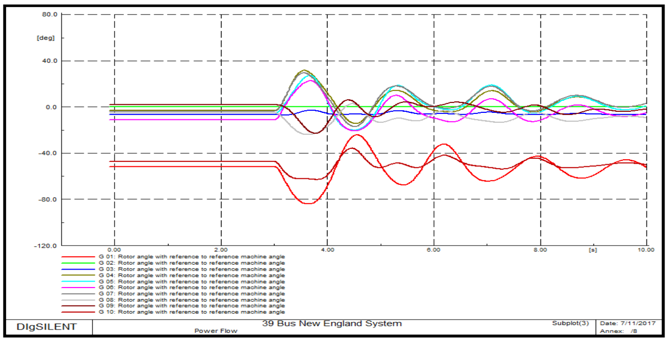

Figure 9: Rotor Angles of all 10 generators in the system with 20% RE

40% RE Penetration level:

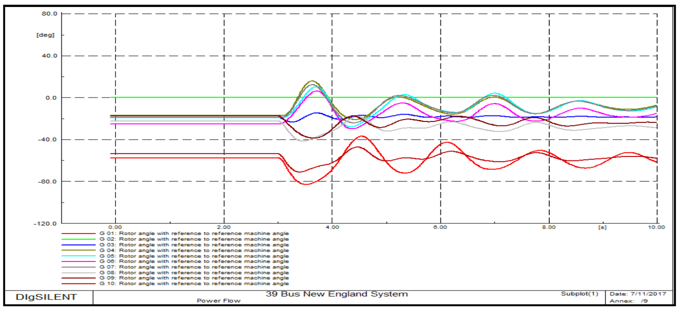

Figure 10: Rotor Angles of all 10 generators in the system with 40% RE

60% RE Penetration level:

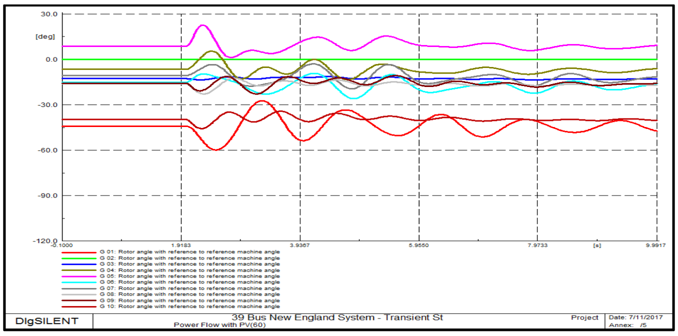

Figure 11: Rotor Angles of all 10 generators in the system with 60% RE

80% RE Penetration level:

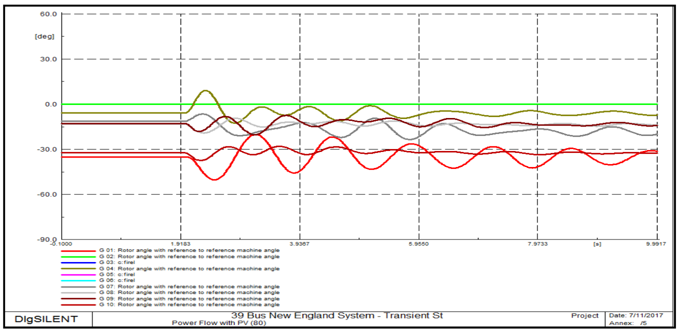

Figure 12: Rotor Angles of all 10 generators in the system with 80% RE

The critical fault clearing times for the above results was also conducted in order to ascertain and quantify the transient stability margins observed on the above graphs. The table below depicts these critical clearing times for the above scenarios.

RE Penetration Level	Faulted Bus	Tripped Circuit	CCT (ms)
Base Case	16	16 - 17	115
20%	16	16 - 17	173
40%	16	16 - 17	257
60%	16	16 - 17	384
80%	16	16 - 17	467

Table 1: Critical Fault Clearing times for different RE Penetration levels

VII. RESULTS ANALYSIS

From the above results it is observed that the magnitudes of the rotor angle swings decrease with increasing RE penetration levels while the CCTs increase with increasing RE penetration levels; proving improving transient stability margins.

This is a clear indication that distributed renewable generation can affect transient stability of a large system in a positive way as it is evident from the magnitudes of the rotor angle swings (more especially first swing) and the critical fault clearing times depicted above that the transient stability margin of the 39 bus system improves with increasing RE penetration levels.

Even though it has been shown through several studies that introduction of RE generation onto power systems erodes system inertia, and hence affects primary frequency control of a network. This is so because system inertia in the context of frequency stability is the aggregated inertia of individual units (synchronous inertia) with the coupling offered by the transmission system and the load. So the effective system inertia gets depleted with increasing penetration of non-synchronous (static) generation sources as synchronous generation sources are displaced hence reducing the aggregated system inertia. The effect is that frequency excursions become more pronounced and severe [5].

However Transient stability of a network is the ability of a network to remain in synchronism following a large event. To put it more prudently, it is the ability of a generator unit/s to remain in synchronism with the rest of the system following a large network event. So the inertia in the context of transient stability is the inertia of the generator in question not “necessarily” the aggregated inertia of the system (which is sum of all synchronous machines with coupling transmission impedances and loads). The above results drive this point home very clearly as the transient stability improves with increasing penetration of static generation; this is because synchronous generators reduce their outputs as RE generators provide more support to the loads. And hence power angle or rotor angle of the machines is less strained as the machines pull back resulting in more improved transient stability margins.

VIII. TEST CASE 2: CONSTRAINED EVACUATION CORRIDORS

In this case a scenario was envisaged where RE generation has to compete for the same evacuation corridor as the conventional generation. The graphs here depict this phenomenon. The RE generation was progressively increased while the conventional generation was kept constant and the network / power corridor was not strengthened. The RE generation was progressively increased to see the impact it makes on the transient stability of the conventional generator by applying a fault on the generator HV bus and tripping one of the adjoining circuits on the evacuation power corridor in question. Selected generators of the 39 Bus system were analysed for this situation.

Gen 01 Rotor Angles:

- 100ms fault at bus 39
- Tripped circuit 39 – 01

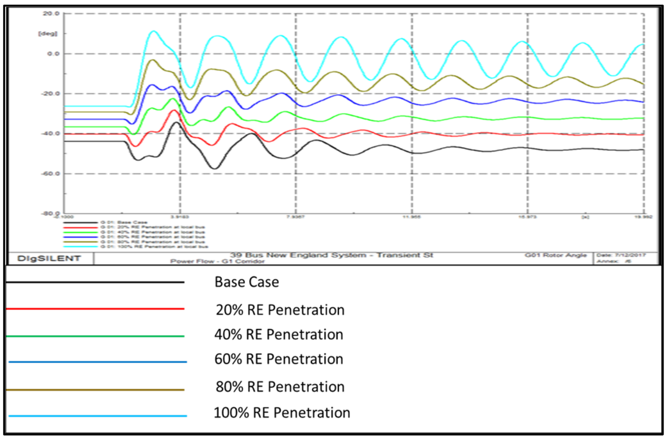

Figure 13: Gen 01 rotor angle as local RE penetration increase

Gen 03 Rotor Angles

- 100ms fault at bus 10
- Tripped circuit 10 - 11

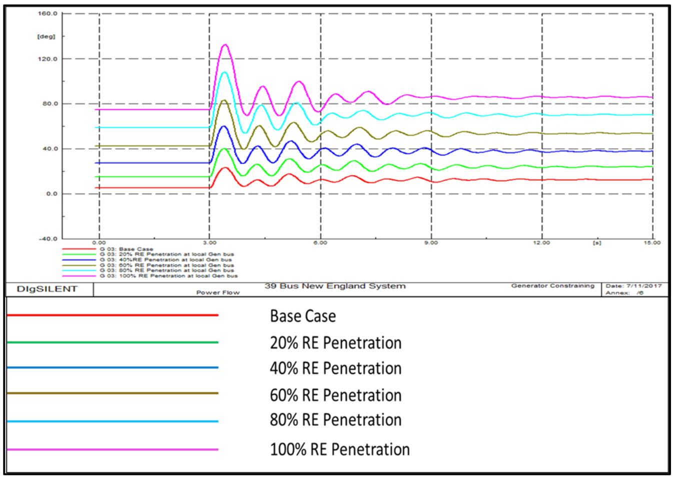

Figure 14: Gen 03 rotor angle as local RE penetration increase

IX. RESULTS ANALYSIS

The above results show that for 100ms fault on the generator bus in question the connected conventional generator transient stability margin is decreased as RE penetration increases at the local conventional generator bus. This is evident from the magnitude of the rotor angle swings as it gets larger with increasing RE penetration on the local generator bus in question. Transient stability margins of concerned generators in this regard decrease because of the constraint on the power evacuation corridor caused by additional RE generation. This situation can be seen on all rotor angles of generators studied above.

X. CONCLUSIONS

The study here shows that distributed renewable generation affects transient stability positively; that is by increasing transient stability margins of conventional synchronous generators in a power system. Distributed RE close proximity to load centres plays a big role in realizing and improving these transient stability margins in a power system. The fact that inertia of a power system is eroded by integration of static RE generation does not necessarily mean that transient stability will be affected negatively as transient stability by its nature is more local as opposed to global (note: the effects of transient instability could cascade to other generators in a system but the problem would have started locally on a specific generator. Hence the problem of transient stability is assessed locally and solved locally).

The study further shows that scenarios that could result in integration of renewable generation affecting transient stability are scenarios that generally reflect poor planning where RE machines are placed such that they introduce constraints on power transfer corridors that were already close to their limits. The afore-mentioned will not be a problem if appropriate studies are done prior to placement of RE generation.

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