Impact of Distributed Generation Penetration on Protection Coordination of IEEE 30 Bus System

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Abstract— In this paper, the effect of addition of distributed generation into the conventional grid on protection coordination of directional over current relays is analyzed. The process of installation of distributed generators such as wind, solar is increasing at a high pace due to the incentives provided by the utility & government. This addition of DGs require re assessment of protection coordination of grid due to the modification in short circuit current levels and bi-directional power flow. The paper discusses the protection coordination of IEEE 30 bus system on Etap 12.6 with addition of distributed generators on some buses. The paper also suggests remedies to avoid mis-coordination of protective devices.

Keywords — Distributed Generation, Protection Coordination, Etap, Synchrophasor

I. INTRODUCTION

THE idea of smart grid has resulted in a shift of paradigm from centralized generation to distributed generation. This paradigm is further expected to enhance with economic incentives [1-2] and with technological advancements leading to more efficient & feasible Distributed Generation (DG) installments. [3].This addition of distributed generation i.e. the generators directly connected to distribution power system with no direct access to transmission system bring many benefits such as islanding mode of operation in case of loss of utility which ensures uninterruptible supply to load in case of loss of utility, decrease in transmission line losses and aid in curtailing the power generation-supply gap. But with many eye striking benefits there are some disadvantages also, among which the heftiest one is the loss of protection coordination of protective relays. [4]

The rapidly increasing shift of generation topology from centralized to distribution has attracted researchers towards the possible effect of DG penetration & the techniques to nullify the mis-coordination caused due to DG. The early researches focused on impact of synchronous DG on system voltage dip & protection coordination [5], its impact using protection Miscoordination index [6], its simulation on Matlab Simulink of a distribution radial feeder [7]. The effect is simulated on IEEE 4 bus system on Etap 7 [8].

Afterwards analyzing the impact of DG, several remedial algorithms were proposed for optimal coordination of protective devices with DG penetration. The techniques used were using voltage accelerated factor for IDMT OCR with no communication requirement [9], optimization of protection using genetic algorithm by solving the problem as constrained non-linear optimization problem of a 3 bus system. [10-11]. Hybrid genetic algorithm is also used for same purpose but for directional OCRs [12]. A particle swarm optimization (PSO) algorithm is used for optimal protection coordination but it's for islanded mode of operation only [13], whereas [14] utilizes hybrid PSO for both modes of DG microgrid operation. Gravitational Search Algorithm used in [15] for optimal minimal time coordination of OCRs proved to be superior then PSO which is simulated on PSCAD/EMTDC. Genetic algorithm (GA), Particle Swarm Optimization (PSA) & Gravitational Search Algorithm (GSA) have been comparatively analyzed on IEEE 34 bus system with max two Distributed generators penetration using MATLAB, and GSA is found to be most optimal in each simulated case [16].

The techniques and algorithms proposed above are rigid i.e. for offline use which require re-assessment of protection coordination of desired system for implementation of optimal coordination schemes. However, later on the research pivot moved towards adaptive algorithms using artificial intelligence to cop up the offline techniques by providing online & self-learning algorithms [17]. An adaptive algorithm is proposed in [18] which requires very less computational power so it can be implemented online. The [18] algorithm was implemented on Real Time Digital Simulator (RTDS). A fuzzy interference & neural network learning module is used for optimal protection coordination of microprocessor based relay online [19].

The most recent advances in the subject enlighten the use of synchrophasor data for protective device PSM & TSM setting in real time [20-21]. The wide area synchronized data when processed on a vector-processor having certain optimization algorithms, yields the optimal parameters for real time implementation on numerical relays.

In this research paper, the impact of DG penetration is first analyzed, Then the maximum DG capacity on each bus is estimated which will not lead to protection Miscoordination. In final section the solution of mis coordination due to DGs is solved using optimal synchrophasor based algorithm.

The impact of distributed generator on short circuit current level depends upon the location, capacity and the type of bus to which it is connected. Therefore, DGs are connected on different bus locations having different power capacity.

II. Effect of High DG Penetration on Power System

The addition of distributed generation to several buses, modify the active & reactive power injection into the lines which in turn modifies the magnitude & direction of current & power flow in normal & faulty conditions. This leads to false & mis-coordinated operation of protection relays. These deterministic effects of DG on protection coordination can be characterized as:

- Loss of Selectivity: The buses with DG will contribute more in short circuit condition which may lead the associated line relays to operate if the fault is not in its zone of protection.
- Loss of Coordination: The operating of relay on Inverse-time curve is based on max fault current ($I_{f,max}$) magnitude but as this $I_{f,max}$ changes the operating point shifts & will lead to quicker or delayed relay operation & in such case the backup protection can operate before the primary one.
- Loss of Sensitivity: The fault current on buses without DG might reduce due to connection of DG on other buses which may lead to reduction in fault current below the pickup of relay, hence the relay loses its sensitivity to detect the fault.

III. The IEEE 30 Bus System

The IEEE 30 bus system is taken as a test case here. A brief description of the IEEE 30 bus system is required so that the effect of distributed generation on different load buses can be easily understood. This system models the American Electric Power System; precisely speaking it models the electrical power system of Midwest of USA in early 1960’s [22]. The transmission lines are modelled as pure resistive as there is no line limits defined in the test case. The one line diagram of the test case system is shown in Fig. 1. [23].

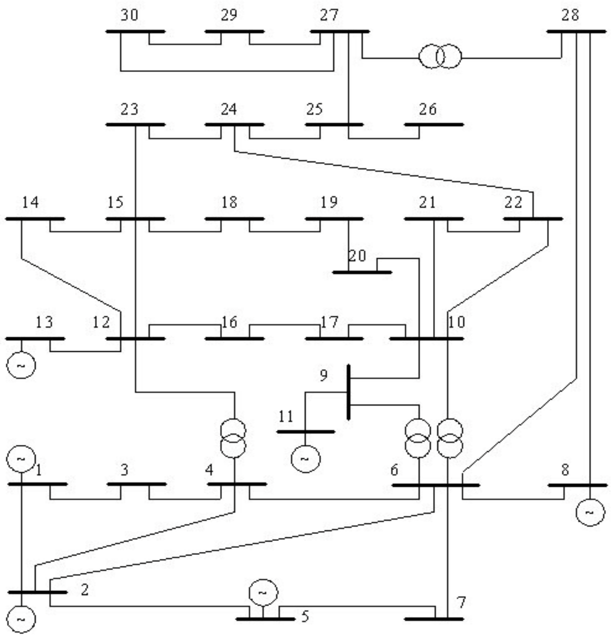

Fig. 1 IEEE 30 Bus System Single Line Diagram

The eight starting buses i.e. bus 1 to 8 are 132 kv buses whereas remaining are 33 kv buses except of bus no. 11 & 13 which are of 11 kv. The bus 11 & 13 are Voltage bus (PV Bus) as voltage control generating units are connected to them. There are only two generators, one of 261 MVA (260 mw) and other of 64 MVA (40 MW). Four synchronous condensers are present on bus no. 5,8,11 & 13. Instantaneous OCRs are used for alternator & load's short circuit protection. Buses are left unprotected as differential protection is used for them which doesn't require time coordination with other relays.

IV. Simulating DG Penetration on ETAP

The effect of distributed generation can be analyzed by connecting generators on load buses (PQ Bus) one by one and then their simultaneous effect. The test case is first protected using simple Over Current Relay-OCR, directional OCR and combined Instantaneous OCR & Inverse Definite Minimum Time (IDMT) OCR are used for transmission line protection. Whereas transformers are protected using differential protection. Siemens 7UT51 percentage differential relay is used for this purpose. Alstom P342 is used as instantaneous & IDMT OCR.

There are three types of generation sources available on ETAP i.e. synchronous machines, Photovoltaic (PV) cells & induction machines. However, the scope of paper deals with short circuit calculations in sub-transient state so synchronous machines are only modelled as Distribution Generation in the test case.

The DG interconnection is first done at Bus 24.

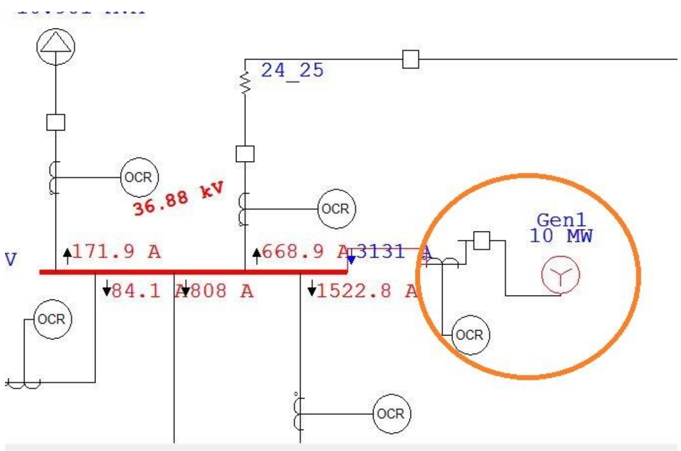

Fig. 2 10 MW DG connected to Bus 24

Due to the interconnection of DG on Bus 24, there are certain mis-coordination events taken place. For example a mis-coordination occurs with the relays connected adjacent to Bus 22 as shown in Fig. 3. The relay 91 pickups before the opening of circuit breaker 67 which is associated with relay 83.Hence, a fault on Line 24_25 caused the line 10_21 to isolate although there isn't any fault on 10_21, so it's clearly a case of mis-coordination. The other events of mis-coordination due to this DG interconnection are also accounted for, in evaluating the Protection Mis-coordination Index (PMI).

Sequence-of-Operation Events - Output Report: shrt_ckt

3-Phase (Symmetrical) fault on connector between CB66 & 21_22. Adjacent bus: Bus 22 3_22

Without DG Data Rev.: Base Config: Normal Date: 09-22-2017

Time (ms)	ID	If (kA)	T1 (ms)	T2 (ms)	Condition
10.0	Relay81	6.376	10.0		Phase - OC1 - 50 - Forward
43.3	CB66		33.3		Tripped by Relay81 Phase - OC1 - 50 - Forward
99.4	Relay83	6.916	99.4		Phase - OC1 - 51 - Forward
101	Relay81	6.376	101		Phase - OC1 - 51 - Forward
124	Relay78	3.473	124		Phase - OC1 - 51 - Forward
133	CB67		33.3		Tripped by Relay83 Phase - OC1 - 51 - Forward
133	Relay91	4.805	133		Phase - OC1 - 51 - Forward
135	CB66		33.3		Tripped by Relay81 Phase - OC1 - 51 - Forward
140	Relay142	1.253	140		Phase - OC1 - 51 - Forward
150	Relay100	1.957	150		Phase - OC1 - 51 - Forward
166	CB71		33.3		Tripped by Relay91 Phase - OC1 - 51 - Forward
167	Relay85	2.922	167		Phase - OC1 - 51 - Forward
174	CB104		33.3		Tripped by Relay142 Phase - OC1 - 51 - Forward
174	CB105		33.3		Tripped by Relay142 Phase - OC1 - 51 - Forward

Sequence-of-Operation Events - Output Report: shrt_ckt

3-Phase (Symmetrical) fault on connector between CB66 & 21_22. Adjacent bus: Bus 22 3_22

With DG Data Rev.: Base Config: Normal Date: 09-22-2017

Time (ms)	ID	If (kA)	T1 (ms)	T2 (ms)	Condition
10.0	Relay81	6.784	10.0		Phase - OC1 - 50 - Forward
43.3	CB66		33.3		Tripped by Relay81 Phase - OC1 - 50 - Forward
99.4	Relay81	6.784	99.4		Phase - OC1 - 51 - Forward
99.4	Relay83	6.941	99.4		Phase - OC1 - 51 - Forward
124	Relay78	3.489	124		Phase - OC1 - 51 - Forward
133	Relay91	4.831	133		Phase - OC1 - 51 - Forward
133	CB66		33.3		Tripped by Relay81 Phase - OC1 - 51 - Forward
133	CB67		33.3		Tripped by Relay83 Phase - OC1 - 51 - Forward
140	Relay142	1.271	140		Phase - OC1 - 51 - Forward
149	Relay100	1.973	149		Phase - OC1 - 51 - Forward
157	Relay85	3.313	157		Phase - OC1 - 51 - Forward
166	CB71		33.3		Tripped by Relay91 Phase - OC1 - 51 - Forward
173	CB104		33.3		Tripped by Relay142 Phase - OC1 - 51 - Forward
173	CB105		33.3		Tripped by Relay142 Phase - OC1 - 51 - Forward
174	CB64		50.0		Tripped by Relay78 Phase - OC1 - 51 - Forward

Fig. 3 Sequence of operation of relay 91

Similarly another such event is observed which is explained using Fig. 3. The mis-coordination due to DG caused nuisance tripping of transmission line 21_22. A fault on line 10_21 near bus 21 caused both the relay 89 & 81 picked up at same time causing both the lines to trip simultaneously.

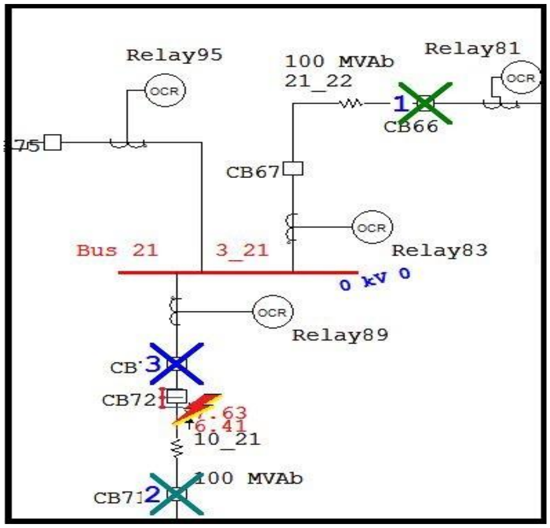

Fig. 4 Relay 81 Nuisance Tripping

This nuisance tripping resulted as a consequence of instantaneous pickup of relay 81. The pickup of relay 81 was set to be 5 KA. This pickup was enough to avoid any mal-operation without interconnection of DG. But after DG connection on Bus 24 the fault level through relay 83 increased to 5.3 KA which caused instantaneous tripping & isolation of line 21_22.

In order to analyze the effect of DG interconnection on protection mis-coordination, the Distributed Generation Penetration Factor (DPF) [24] defined in eq. (1) is plotted against the Protection Mis-coordination Index (PMI) [25] defined in eq. (2).

$$DPF = \frac{DG\ connected\ to\ Bus\ (MW)}{System\ Load\ (MW)} \cdots (1)$$

$$PMI = \frac{Miscoordination\ events}{Total\ Fault\ Events} \cdots\cdots (2)$$

The system load is around 300 MW which is generated by the only two generators in the system. The DPF is calculated using this. Whereas the max DG rating goes up to 10 MW. The total fault events which can take place due to DG interconnection on Bus 24 is thirteen. After connection of DG maximum two miscoordination event occurred. As the capacity of DG increased from 0 to 10 MW in step size of 100 KW, it is found that first miscoordination took place at 410 KW DG while the second & last on 9.2 MW DG rating. The DG connection [24] vs protection mis-coordination index [25] is shown in Fig. 5

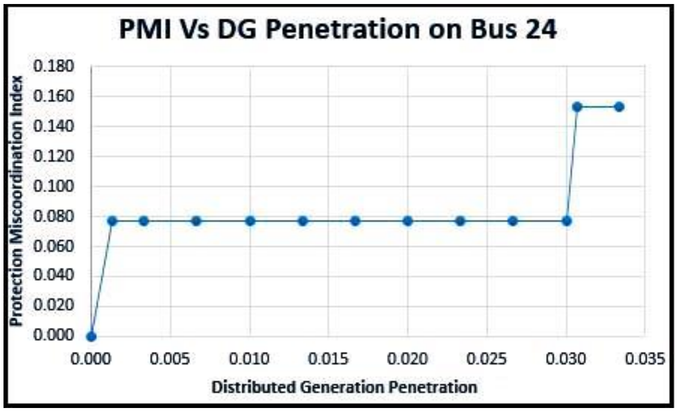

Fig. 5 PMI Vs DPF on Bus 24

Similar approach is used for all other buses of 33 & 11 KV, due to the fact that distributed generation can be connected to only Low or Medium Voltage with no direct access to High Voltage Transmission Network. Bus number 1 to 8 & 28 are 132 KV so, DG is connected to all buses except the mentioned above. Fig. 6,7,8,9 & 10 reveals PMI Vs DPF simulated using DG penetration on remaining buses.

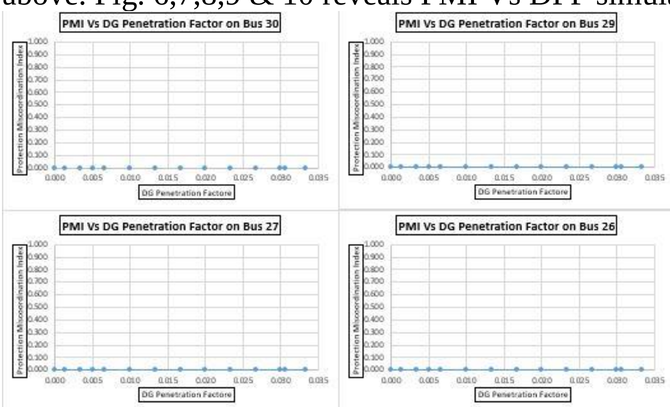

Fig. 6 PMI Vs DPF-Bus 26 to 30

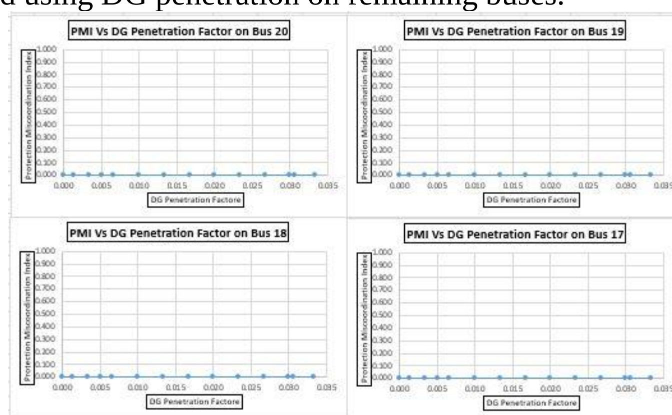

Fig. 8 PMI Vs DPF on Buses 17 to 20

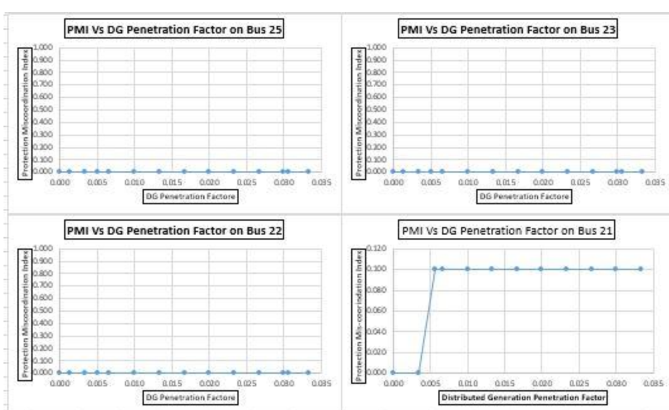

Fig. 7 PMI Vs DPF-Bus 21, 22, 23, 25

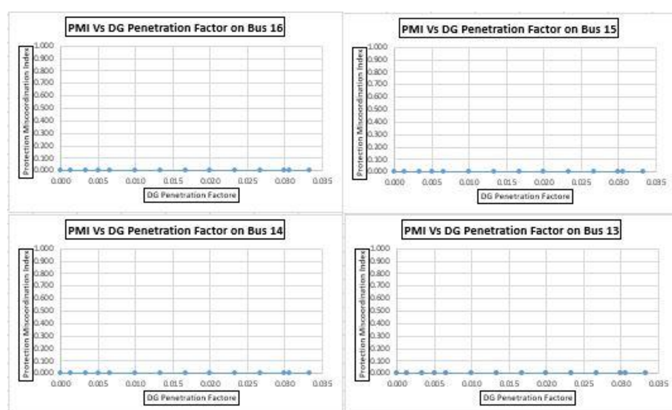

Fig. 9 PMI Vs DPF on Buses 13, 14, 15 & 16

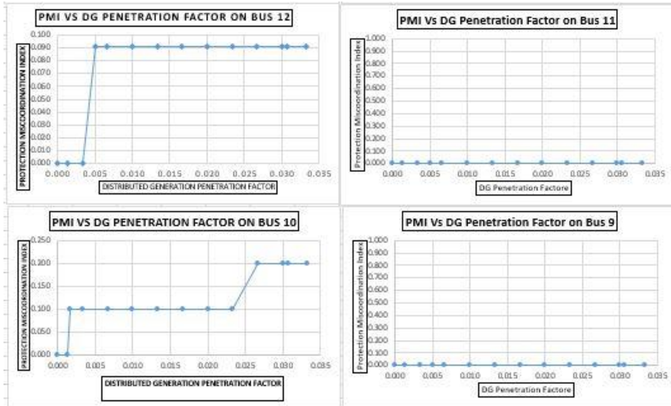

Fig. 10 PMI Vs DPF on Buses 9, 10, 11, 12

V. Analysis of Simulated Cases

It can be seen from the analysis that the DG penetration has no effect in several buses. It is due to the fact the IEEE 30 bus system is a complex meshed network instead of a simple radial distribution feeder. In radial system the power flow in uni-directional, hence the protection system is designed for accordingly, whereas the meshed IEEE 30 bus system is already a bi-directional system to increase reliability of the system. Hence, the addition of DG in a radial network alters the power flow direction & also its magnitude, which in turn disturbs the protection coordination. Whereas, the addition of DG in a meshed network doesn't alter the direction of power flow as the bidirectional flow has already been considered during design of protection coordination. As a consequence very few mis-coordination event have been observed.

VI. Highest Value of DG which Doesn't cause Miscoordination

The results of the simulated cases depicts the maximum value of distributed generation which can be connected on respective buses. Bus no. 1 to 8 and 28 are 132 KV buses so there isn't any question of DG penetration on these buses. The effect of DG interconnection is analyzed on 33 KV & 11 KV buses. It has been observed that there is no Miscoordination occurred on bus no. 9, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 22, 23, 25, 26, 27, 28, 29 and 30. Mis-coordination is observed on Bus 10, 12, 21, and 24. The findings from the simulation gives value of maximum DG interconnection capacity allowed on respective buses are:

- Bus 10: 500 KW
- Bus 21: 1700 KW
- Bus 12: 1500 KW
- Bus 24: 410 KW

The same is shown in Fig. 11.

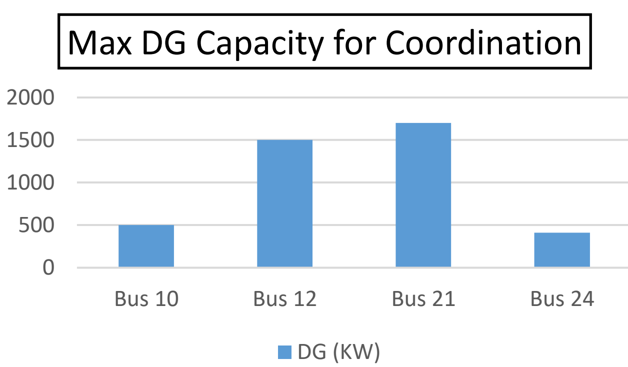

Fig. 11 Max DG Capacity which does not disturb Protection coordination

VII. CONCLUSION

It is concluded that distributed generation doesn't have substantial impact on protection coordination of transmission system due to its inherent characteristics. On the contrary, a radial distribution feeder's protection coordination is severely affected due to DG. Although there is no mis-coordination on a transmission system up to a certain limit, but the effect of DG cannot be completely ignored. The coordination studies reveal the maximum DG limit which can be safely interconnected without causing mis-coordination, either a DG below this limit should be connected or a re-assessment & re-designing of protection coordination is required, whatsoever is more economical. In recent years, the use of synchrophasor has made this re-designing & re-assessment possible in real time using real time state models. The scheme has already been implemented in several transmission networks and is further expected to be implemented on distribution network also, so that contribution of renewables & other distributed generation in energy mix will be increased.

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