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A Self Healing Methodology for Economic Integration of Wind Farms to Modern Power Networks

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Abstract - This paper presents a differential evolution (DE) based methodology to relieve congestion and improve quality and cost efficacy of generated power ,formulating a 'penalty based congestion constrained OPF problem' in a hybrid thermal-wind power farm . To satisfy the need of future demand , in view of the growing concern over industrial impact of conventional power plants, the main hindrance in application of Wind power plant apart from uncertainty is its elevated cost. Employing an approach of 'Demand sensitive loss factor' (DSLF) to select the worst possible inadvertent states of the system and the weakest bus of the system in active, reactive loading the algorithm attempts to reschedule the generators to bring down the individual line flows to provide better congestion management keeping in view of minimization of the cost of generation and the line losses not only at normal condition but also stressed loading condition and contingency cases. The results also illuminate a profitable economic situation in favor of proposed system at increased loading where total line loss decreases and total cost in conventional and proposed system converges, also not to forget the better operating conditions in comparison to conventional system. The efficiency of the proposed system has been tested on a modified IEEE 30 bus benchmark system.

Keywords - *Proposed System, Demand Sensitive Loss Factor (DSLF), Operating Conditions, Differential Evolution.*

I. INTRODUCTION

Over a few decades the world is exhibiting a strong concern over the environmental impact and preservation of conventional energy sources. Also boosting development in various part of the world and surging power demand are forcing the transmission lines to operate at optimum loading stress .In a lot of modern power systems renewable energies, especially wind power revealing as main drivers for the actual restructuring of transmission and distribution systems for reliability and comparative cost effectiveness. The prime objective of the acid test with wind power is to escalate the quality of supply, system security and stability keeping sufficient profit margin. But the uncertainty of wind power generation, grid constraints and price responsiveness makes the incorporation of wind power plants a mammoth task so far as power system operating constrictions are concerned. To satisfy the needs of the future, the scholars all over the world are trying to find a solution by formulating Optimum power flow (OPF) problem, in pursuit of resolving the crisis. The most common of them are employment of a suitable algorithm to optimize the installation of IR (Intermittent Resources) to maximize firm sales [1], but it does not throw any light on the price responsiveness of the market and performance indices. It is true that there is an uncertainty of wind generation and the same has been attempted to be reconciled by using probabilistic concept of confidence interval in artificial neural network based wind forecast model [2], but the application of the work in the present market scenario and different methods to store the generated electricity for future demand hours, still remained un-revealed. In [5] a new approach for unit commitment (UC) where the system reserve requirements and the wind power availability constraints are realized but the literature defies on the physical application and profitable face of wind energy adaptation. In the proposed platform we can intelligently develop a stochastic framework which leverages distributed storage, thus alleviates many of the problems of current grid [9]. [12] presents an improved algorithm for transmission expansion planning based on ant colony optimization to use a constructive heuristic to find acceptable solutions in an early stage of the search process [2] but does not produce enough detailed experimental result to support the augmentation of wind power plants. In [13] a mathematical model to derive the best offering strategy for virtual power plant (VPP) that aggregates wind power and flexible load in an electricity market is proposed which is a remarkable and replicable approach. [14] & [18] employs a wind farm, direct heating and a gas turbine driven synchronous generator whose outputs are combined before connecting to the grid but the paper does not illuminate the modern relevant issues like the voltage profile stability or congestion management along with cost effectiveness . [16], [21] & [28] models the load and generation of two micro grids with wind farms as VPP to implement OPF using particle swarm optimization (PSO), without any comparative study with traditional system. In light of that [24] & [25] follows the concept of VPP, by aggregating distributed energy resources that communicate with decentralized energy management system where the technical aspect of operation would be covered and participation of DG in the power market would be facilitated. [27] Compares various models of steering strategies for a portfolio of Distributed Energy Resources (DER) to guide each DER in order to dispatch desirable active power, but to attain this objective it sacrifices the economic consideration.[17] performs all system control while maintaining system security.[19] & [20] combined the theory of hybrid power system incorporating wind and depicted the power and gas load curves in technical and economical point of view. The literature also demonstrates the reduction of emissions of the polluting gases which strengthens the core of our present work. [26] cited that the integration of distributed generation (DG) and renewable energy sources (RES) in the passive controlled distribution networks leads in present situation to an expansion of the network capacity and thus to excessive investments, but the paper missed to express its effectiveness at increased active and reactive loading stress. All these approaches definitely illuminated different spheres of wind firm integration under limited number of operating constraints, but the need of a multi-objective optimisation can be still felt which takes all the operating constraints of modern power system into account for worst possible inadvertent states of the system. Hence The present work proposes to relieve congestion and improve quality and cost effectiveness by formulating a 'penalty based congestion constrained OPF problem' and solving the same using Differential Evolution technique. The multi-objective OPF solution attempts to reschedule the generators in such a way that the individual line flows are brought down to a desired level, not exceeding their loadability limits while paying equal or optimal emphasis on minimization of the cost of generation and the line losses and most importantly the cost involved in managing the congestion (commonly termed as the 'congestion management cost)at not only normal condition but also stressed loading condition and contingency cases. The effectiveness of the proposed algorithm has been demonstrated on a modified IEEE 30 bus system for worst possible contingencies and loading stresses. The prudent effect of the results indicate that the method proposed in this paper is not only efficient in managing line congestion but they are also profitable in economical point of view at high active and reactive power loading where total line loss decreases and total cost in conventional and proposed system converges with wind power plant integration. The proposed method also provides better management of bus voltage profile and improves the security of the system in the event of the pits of contingencies.

II. THEORY

From [1],[2]&[3] we observe that wind farm can be modeled in 3 different forms i.e. a)**PQ**, b)**PX** & c)**RX** in **PX** model the real power generated and nonlinear magnetizing reactance is known and in **RX** model the nodal resistance and nonlinear magnetizing reactance are known but as the magnetizing reactance is inconsistent due to the variation of the saturation characteristics , the implication of these models may not be same for all the machines. But in **PQ** model active power and reactive power are kept as base parameters (depending on the asynchronous generators characteristics) hence results obtained from **PQ** model can be more decisive.

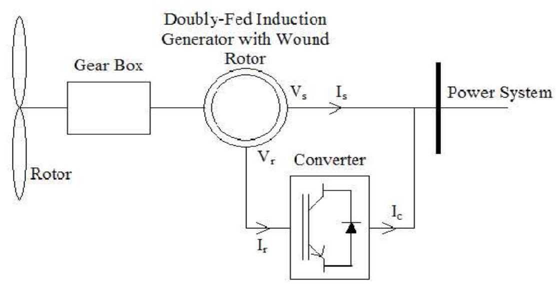

Fig 1: Doubly Fed Induction Generator

A. PX Model of an Asynchronous WT: PQ Model of an Asynchronous WT:

In this modeling of wind farm the real power (P) produced by the stochastic method adopted assists in determining the reactive power (Q) consumed. Improvements on P-Q model can be achieved if the steady-state model of the induction machine is considered fig 2.

From [21] expression of reactive power is given by the subsequent and it is positive when consumed by the bus

$$Q = V^2 \frac{(X_c - X_m)}{X_c X_m} + X\frac{(V^2+2RP)}{2(R^2+X^2)} - X\frac{\sqrt{(V^2+2RP)^2-4P^2(R^2+X^2)}}{2(R^2+X^2)} \quad (1)$$

An approximation of the above expression can be made from the [21]:

$$Q=V^2\frac{(X_c-X_m)}{X_cX_m}+\frac{X}{V^2}P^2 \quad (2)$$

Where, Q is the reactive power consumed, V is the voltage, P is the real power, X is the sum of the stator and rotor leakage reactance, X_c is the reactance of the capacitors bank, and R is the sum of the stator and rotor resistances, X_m is the magnetizing reactance.

The benefit of the **PQ** model is that the maximum limit of real power generated is calculated as a function of the wind speed for the first iteration of the power flow analysis, and from then on its value remains as a constant for the subsequent iterations. It can be seen from the above expression that the consumed reactive power is a function of real power generated and the bus voltage. As because the real power is assumed to be constant, the only variable is the bus voltage.

In this paper the proposed system is designed in **PQ** model and the following induction generator model () has been adopted with X_m=1.8212Ω,X_c=31.85Ω and X=0.0722Ω

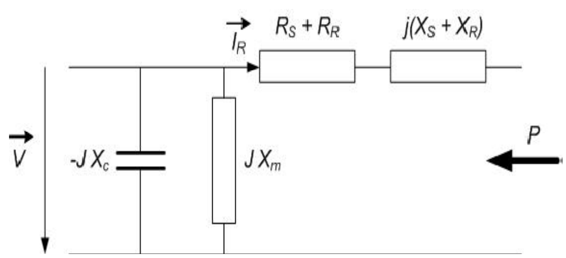

Fig 2: Equivalent circuit diagram of an Induction Generator

B. Problem Statement:

Objective function in a conventional cost optimization problem can be described as:

$$\text{Minimize } F=\sum_{n=1}^{N_G} C_T \text{ \$/hr} \quad (3)$$

$$C_i = AP_{gi}^2 + BP_{gi} + C \quad (4)$$

N_g=No of generators, A, B, C = cost co-efficient of generators, P_{gi} = generation of i^{th} generator in MW.

In the present work, the objective function is suitably modified to incorporate the proposed voltage, line loss and congestion penalties.

Minimize:

$$F=\sum_{i=1}^{N} C_i + (TL-TL_{max})*P_1 + (V-vv)*P_2 + LF_{mcx}*P_3 \quad (5)$$

Where,

TL_{max}=Maximum Line Loss

vv= Minimum Bus Voltage

V=Bus Voltage

LF$_{max}$= Maximum line flow

P_1=Penalty for Total line Loss of the System

P_2 = Penalty for Minimum Bus Voltage of System

P_3= Penalty for Maximum Lineflow

The objective function in this paper is to minimize the overall cost of the of generation and as well as to get most economic generating pattern.

The constraints are common for both the objective functions and are described as follows:

1. *Equality or power balance constraints:*

$$\sum_{i=1}^{n} P_{Gi} = P_D + P_L \quad (6)$$

Where, P_g =Generated real power, P_d =Real power demand, P_l=Real power loss

2. *Inequality Constants are assumed same in both systems:*

- Voltage Constraint at buses:
  $V_{imin} \leq V_i \leq V_{imax}$
- Power flow constraints at branches:
  $P_{imin} \leq P_i \leq P_{imax}$
- Generator reactive power constraints:
  $Q_{G_imin} \leq Q_{G_i} \leq Q_{G_imaX}$

Where, P_{gi} , Q_{gi} = Active and reactive power of generator i respectively, P_{gi}^{min} , Q_{gi}^{min} = Lower limit of active and reactive power of the generators, P_{gi}^{max} , Q_{gi}^{max} = Upper limit of active and reactive power of the generators

Demand sensitive loss factor (DSLF):

The effect of loading stress and contingency is different for different buses. The reactive and contingency sensitive indices are available in (Ref:

[19]). The active power loading index can be expressed as demand sensitive loss factor. It is defined as

$$\mathbf{DSLF} = \mathbf{P_L/P_D} \text{ or in dynamic form } \mathbf{DSLF} = \Delta \mathbf{P_L/\Delta P_D}$$

$$\sum_{i=1}^{n} \Delta P_{Gi} - \Delta P_L = \Delta P_D$$

$$\text{Therefore, } \Delta \mathbf{P_L}/\Delta \mathbf{P_D} = \sum_{i=1}^{n} \Delta \mathbf{P_{Gi}}/\Delta \boldsymbol{P_D} \mathbf{-1} \quad (7)$$

Active Power Loading has a direct impact on line loss. To cater the increased demand the line flows are altered resulting in a corresponding rise in demand. In this respect DSLF can be utilized as a simple and effective means to identify the weak, weaker and weakest sensitive buses of active power loading stress. In simulation this proposed factor has been employed to select the worst possible inadvertent states of the system. The table depicts the variation of DSLF for a 10% active loading stress in all the load buses. On observation, it can be inferred from the table that bus 30 poses highest value of DSLF and hence it may be treated as the weakest bus in terms of active power loading.

Identification of most vulnerable lines in terms of demand sensitive loss factor (DSLF):

TABLE1: INFLUENCE OF THE BUSES ON INCREMENT OF LOAD

Bus No	Normal Load	Increased Load	Loss	P_L/P_D
3	2.4	30.74	10.4637	0.0986
4	7.6	35.94	16.2497	0.1152
6	0	28.34	5.362	0.0909
7	22.8	51.14	7.3076	0.1249
9	0	28.34	10.2059	0.0909
10	5.8	34.14	5.1133	0.1095
12	11.2	39.54	4.7871	0.1268
14	6.2	34.54	11.3479	0.1107
15	8.2	36.54	16.6194	0.1172
16	3.5	31.84	16.7864	0.1021
17	9	37.34	4.0998	0.1197
18	3.2	31.54	14.5028	0.1011
19	9.5	37.84	11.7949	0.1213
20	2.2	30.54	11.4142	0.0979
21	17.5	45.84	7.4143	0.1470
22	0	28.34	5.7325	0.0909
23	3.2	31.54	16.6722	0.1011
24	8.7	37.04	5.4924	0.1188
25	0	28.34	17.0085	0.0909
26	3.5	31.84	11.2608	0.1021
27	0	28.34	16.0211	0.0909
28	0	28.34	15.6982	0.0909
29	2.4	30.74	15.2205	0.0986
30	10.6	38.94	20.3308	0.1640

C. Flowchart of the proposed Algorithm

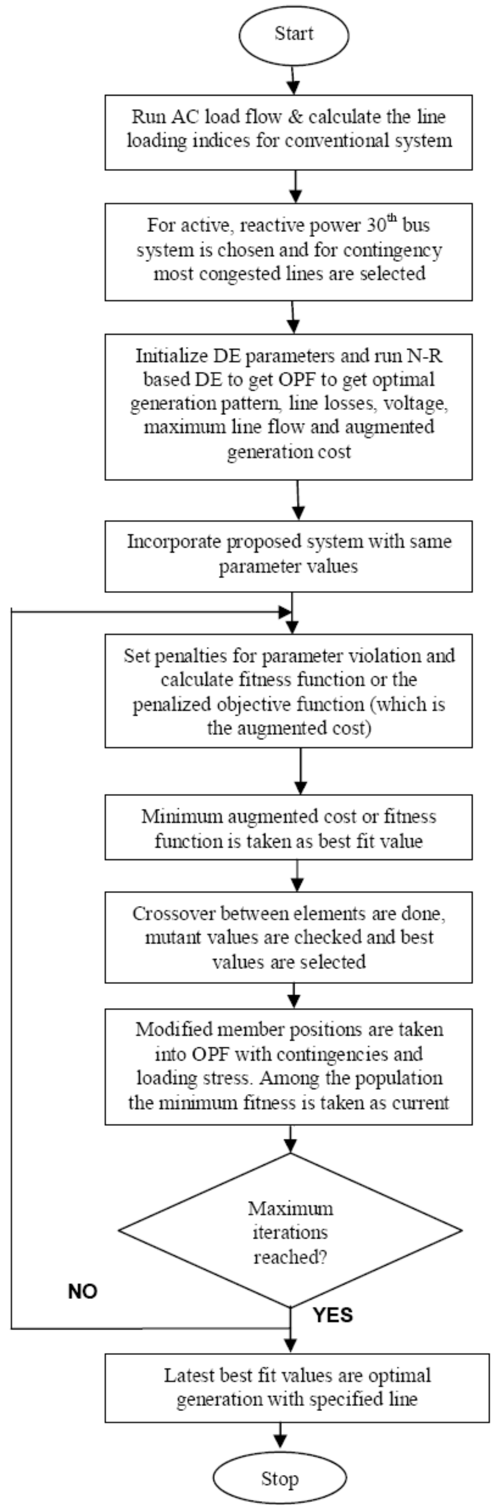

Fig. 4: Flowchart of the algorithm

III. SIMULATION AND RESULT

A. System Description:

The feasibility and effectiveness of the incorporation of the renewable energy sources has been tested with a standard IEEE 30 bus system. A brief description of the system is given in Table 1 while Table 2 carries the cost coefficients employed in optimization. Table 2 depicts the information of the cost coefficients of the wind generator units.

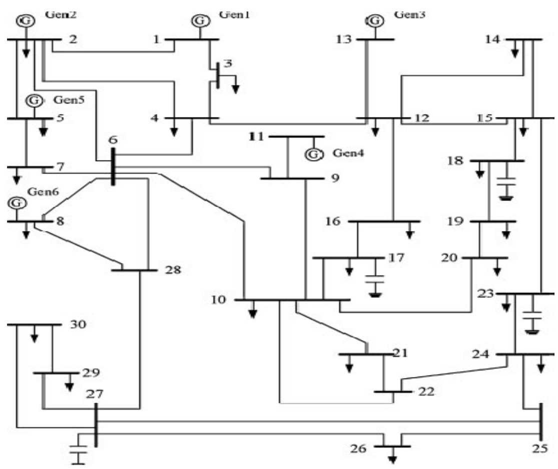

Fig. 3: The standard IEEE 30 bus system

Table 1: Description of the test system

SL NO.	IEEE 30 BUS SYSTEM	
	Variables	**AdoptedSystem**
1	Branches	41
2	Generators	6
3	Total Demand(MW)	283.6

Table 2: Generator Cost Co-efficient with Thermal Units

Bus no	Real Power output limit in MW		Cost Co-efficient		
	Min	*Max*	*A (US$/MW²)*	*B (US$/MW)*	*C (US$)*
1	50	200	0.010	0.300	35
2	20	80	0.020	0.600	60
5	15	50	0.070	0.095	45
8	10	35	0.090	0.025	30
11	10	30	0.020	0.600	60
13	12	40	0.070	0.095	45

Table 3: Generator Cost Co-Efficient of Thermal and Wind (Bold Faced) Generators[20]

Bus no	Real Power output limit in MW		Cost Co-efficient		
	Min	*Max*	*A (US$/MW²)*	*B (US$/MW)*	*C (US$)*
1	50	200	0.010	0.300	35
2	**20**	**80**	**0**	**0.00083**	**256.8**
5	10	35	0.090	0.025	30
8	**15**	**50**	**0**	**0.00083**	**256.8**
11	10	30	0.020	0.600	60
13	12	40	0.070	0.095	45

B. Simulator Description:

The classical OPF approach may not be suitable due to non linearity of the objective function of the proposed algorithm. Hence to obtain most feasible solution a stochastic evolutionary algorithm has been adopted. The parameter setting of differential evolution has been depicted in the table below:

Table 4: Simulator description

Particulars	**Value**
Value To Reach, VTR	1.e-6
Number of parameters of the objective function, D	n-1 (n=number of Generator present)
Number of population members, NP	20
Maximum number of iterations (generations),itermax	50
DE-stepsize F ex [0, 2],F	0.8
Crossover probability constant ex [0,1],CR	1
strategy	1

C. Base Case:

For efficient comparison a system with all thermal units and a hybrid system with 2 wind and 4 thermal units has been modeled in 30 bus system according to table 4.In the base case both the systems with their respective OPF objective has been subjected to OPF.The results of the two simulations in terms of total cost, Min bus voltage, Max line flow and Total loss have been shown in table[4],even though the proposed system has been subjected to a high degree of operational cost, the other parameters however showing improvements at operating conditions.

Table 5: Comparison between traditional system & proposed System

Particulars	All Thermal System	Proposed System
Cost	801.82	1023.67
Min. Bus Voltage	0.9957	0.996
Max. Line Flow	118.62	105.87
Total Loss	9.4022	4.988

D. Reactive Loading Stress:

Table 6: Cost Variance with Reactive loading Stress

Reactive Load(MVAr)	All Thermal System	Proposed System
1.9	801.82	1057.1
6.9	802.45	1070.4
11.9	903.68	1216.4
16.9	908.64	1325.5
21.9	912.89	1436.0

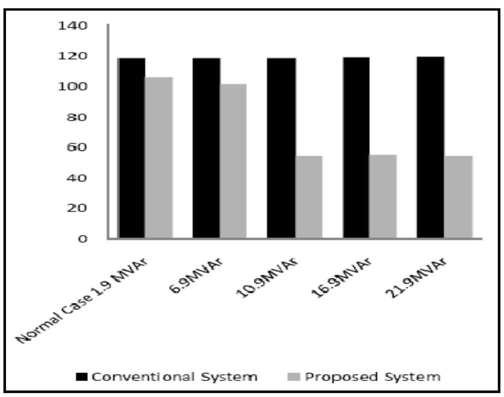

Fig 4: Maximum line flow vs. Q

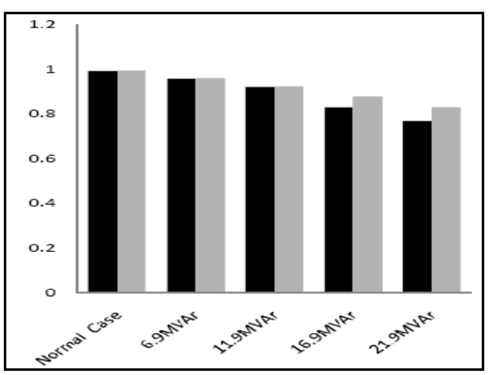

Fig 5 : Minimum Bus Voltage vs Q

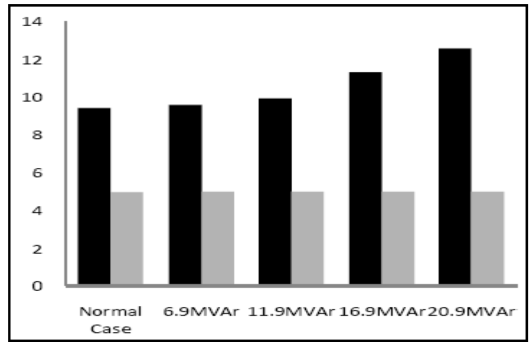

Fig 6: Loss vs. Q

The dreadful impact of reactive loading stress is on Bus voltage profile of the system apart from causing congestion and increased line loss. From the above figure no.4 it can be inferred that maximum line flow in case of the proposed system has shown a declination with respect to the conventional (all thermal) system, thus congestion is managed. even in case of worst possible reactive loading of the system. The minimum bus voltage of proposed system has been subjected to an effective escalation with respect to conventional system, resulting an improvement of power transfer capability. The proposed system also projects better system functioning with the case study implemented with a reduction of line loss

E. Experimentation on Contingent states of the system:

Table 7: Cost Variance of Contingent states

Line Tipped	Cost (All Thermal System)	Cost (Proposed System)
(2-4)	804.0127	1368.7
(2-4) & (3-4)	824.6608	1187.9
(2-4),(3-4)&(5-7)	826.5266	1051.7
(2-4),(3-4),(5-7)&(4-6)	829.0310	1084.9
(2-4),(3-4),(5-7),(4-6)&(6-8)	829.0310	1387

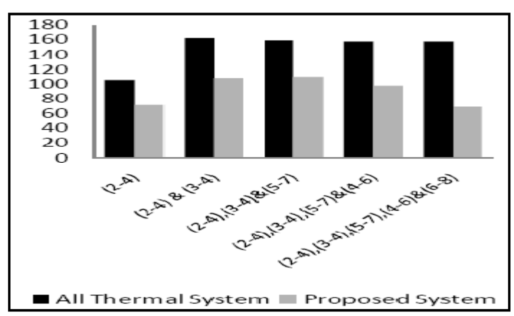

Fig 7: Maximum line flow (contingency)

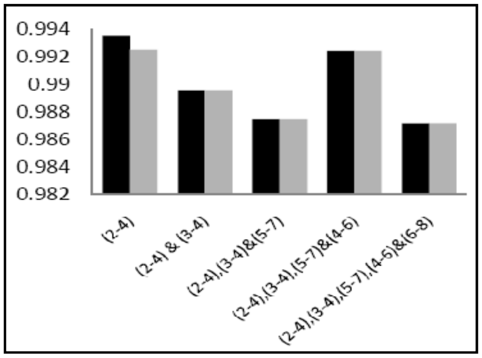

Fig 8: Minimum bus voltage (contingency)

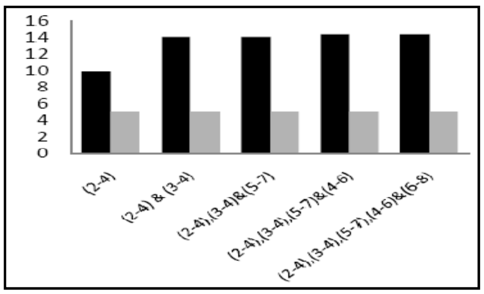

Fig 9: Total Loss (contingency)

By taking different lines of the system as subject of outage in increasing order of degree of contingency(n-1,n-2,n-3,n-4,n-5) for the conventional and proposed system, an expected higher cost has been obtained for the proposed system, but following cases depicts better performance for the latter system, which satisfies primary objective of this work. Line flow value also responded positively. This gives future provision for increased demand managing congestion .The Voltage and loss profile of the system has also been subjected to an improvement. This establishes the self-healing capability of the proposed system during contingency.

F. Active Loading Stress:

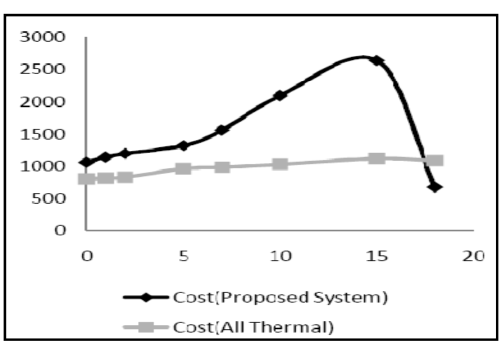

Fig 10: Line Chart comparing cost of two systems

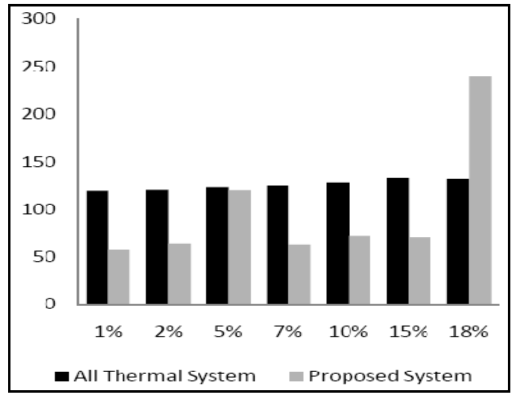

Fig 11: Maximum Line flow vs. P

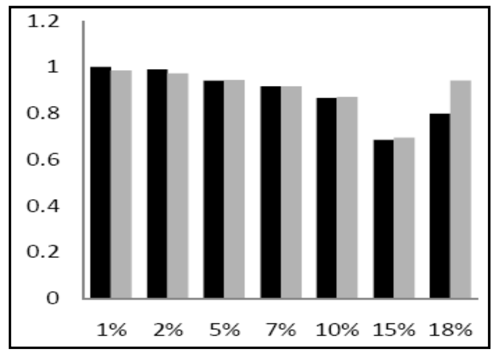

Fig 12: Minimum bus volt vs. P

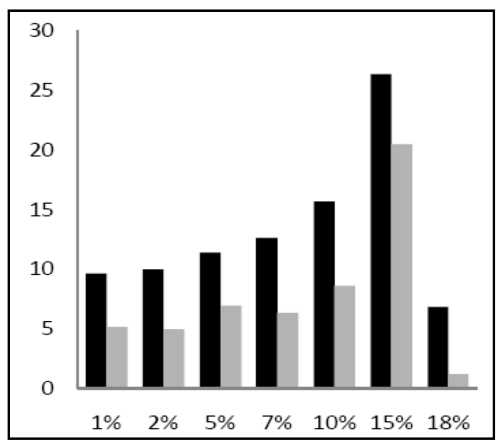

Fig 13: Total Loss vs. P

For active loading stress, the maximum line flow values for proposed system show that future demand could be met and congestion is managed in a far better perspective which strengthens the prima facie. Again total line loss for proposed system shows satisfactory decreased values for loss with active loading stress, so system stability and performance is improved.

IV. CONCLUSION

Due to socio-economic reasons, power markets round the globe have bifurcated towards alternative solutions of energy production. The proposed system is an endeavor of economic integration of one such alternative sources (wind power)into the conventional grid. With the proposed algorithm, the system has been demonstrated to work proficiently in active, reactive loading and worst possible inadvertent states of the system. For the identification of the weakest zone in terms of loading stress, an index named DSLF has also been proposed. For effective profusion of renewable energy sources with the conventional thermal power plants, the proposed methodology can be recommended to the system operators for better operating conditions, stability and cost efficiency.

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