STRENGTH OF STANDARD IEEE POWER SYSTEMS : A REVIEW

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Abstract : Bus is an important component of power system. Weak voltage profile of buses is a serious problem in power network which can harm the security and reliability of power system. Whenever there is a change in load, the system voltage level changes. The demand of reactive power in power system increases With the drop in voltage level. If the reactive power demand is not met, then it leads to further decline in bus voltage resulting in the cascading effect on adjacent power networks. Hence determination of the strength of buses and maintaining the voltage profile within permissible limits becomes essential. This paper reviews various problems faced by power systems due to weak voltage profiles and its solution for a better , reliable power supply in wide area power systems. This review paper presents algorithms for load flow solutions and their advantages, disadvantages ;Indian Electricity Rules for permissible fluctuation of voltage ; top view of IEEE 57 ,118,300 Bus test system constructed in Power World software ; improvement of voltage profile and power flows after inserting series capacitor in the IEEE 57 bus test system and strong and weak bus voltages of IEEE 118 and 300 bus test systems after running NRLF.

Keywords – Bus , Newton-Raphson load flow , Strongest bus , Weakest Bus ,Voltage profile , Power flow .

1.INTRODUCTION

Bus bar in a power system is a metallic strip responsible for conducting electricity in a substation ,electric grid , battery bank or other electrical apparatus. Bus bar is usually made of copper ,brass or aluminium. Bus bar are of variety of shapes .e.g.- flat strips , solid or hollow tubes etc. Bus bar should be robust enough to support its own weight ,mechanical vibrations and earthquakes also .Bus bars are typically placed inside switchyard ,control panels etc.Busbar should have proper insulators . In substations mainly two bus system is used . The concept of two bus system is like that every feeder of the two bus system is connected with two different busbars.e.g- Main bus system and transfer bus system . The main bus is connected to each feeder through a circuit breaker . One bus coupler couples main and transfer bus through a circuit breaker and isolator . Voltage profile in bus bars in Wide Area Systems is an important parameter w.r.t the security and reliability issue of the power system. Whenever there is a change in load the system voltage level changes. With the drop in voltage level, the reactive power demand increases. If the reactive power demand is not satisfied , then it leads to further decline in bus voltage resulting in the cascading effect on adjacent power systems [1,14-15]. So, maintaining the voltage profile within permissible limits becomes necessary and essential [1].To improve the voltage profile series capacitor is used in the circuit. It increases active power transfer capability and supply some portion of reactive power also [2,7,11,12,13,19-20]. To control the reactive power synchronous motor is used at distribution level or 132 KV level , shunt inductor is used at 400 KV , 765 KV ,1000KV and 1200 KV at the receiving end substation . Inductor is preferred to account the possible Ferranti effect voltage at light load conditions[15] . Voltage control devices (e.g- Shunt Capacitor , Synchronous motor , FACTs devices) are usually placed at load station . A true load station does not have capability to control the reactive power. Hence , it is called a PQ bus . But a load bus is a

reactive power control element and have the capability to maintain voltage profile to control reactive power and maintain voltage profile. This type of bus is called voltage controlled bus [13].

1.1 Load Flow Study

– Load flow referes to the calculation of (V and δ) complex bus voltages , h such that all buses except slack bus subjected to the given loading conditions , enforcing Q limits , tap limits and tie line power flow limits [7].

Usually a centrally located large generating station is selected as slack bus (or swing or reference bus).

Voltage profile or power transfer capability can be improved by inserting capacitor between relatively weak voltage buses of a Wide Area system. This process not only affect the buses between which the capacitor is placed but also has a cascading effect in the whole network .Specially adjacent buses of sending and receiving end sides are mostly affected .By improving the voltage profile the reliability, stability and security of the system is largely improved.

Tajudeen et al., [2] proposed improvement of voltage profile by applying concepts of circuit theory and by Y-admittance matrix on networks. Eigen value decomposition and partitioned Y-admittance matrix determines the location for VAR compensators. Buses associated with smallest Eigen value have dominant influence on entire voltage of network on the basis of inversely proportional relation existing between bus voltage and Eigen values. This reveals the highly suitable locations for allocating VAR compensators .State variables of VAR compensators are consisted in load flow techniques and hence power flow solution can be used to determine the appropriate compensators sizes [1].

Most of the problems faced by the power system can be resolved by internal relationship among its parameters . Tajudeen et al., [3] have discovered the characteristic indices based on inherent structure using partitioned Y-admittance matrix. Ideal generators, affinity of generator and effect of structure on generator and load electrical attraction regions have contributed for the value of the indices. With the indices generator locations can be specified to inject maximum real power in the power system .

For solution of load flow problem , the linear equations can be solved directly by several methods .e.g.- Cramer's rule , Inverse technique , Gauss seidel method , Cholesky method etc .
The several iterative techniques for load flow study are :

a) Gauss method
b) Gauss Seidel method
c) Newton – Raphson method (NR method)
d) Fast – Decoupled method

Out of the above methods ,NR method is used in our work. We feel it is the best out of the lot [13].

1.2 Well conditioned and ill-conditioned system-

A power system is characterised as well conditioned system w.r.t good X/R ratio and good convergence characteristics. Usually a well conditioned system having X/R ratio more than 5. Highly mesh connected or interconnected systems usually have all the above properties. Hence they are treated as well-conditioned .But distribution network is highly radial system and it has low X/R ratio and exhibits poor convergence characteristics .Therefore they can be treated as ill-conditioned system [8]. An ill-condition system having X/R ratio maximum 1-2 , or even below 1.

1.3 Gauss Method -

In Gauss method, initially we have to start with a guess voltage .$(k+1)^{th}$ value of iteration can be calculated using below formula [6-7]:

$$\mathrm{E_P}^{K+1} = \frac{1}{Y_{PP}} \left[\frac{P_P - jQ_P}{E_P^{k*}} - \sum_{\substack{P \neq q \\ p=1}}^{n} Y_{pq} \ E_q^k \right] \quad (1)$$

K is the previous iteration count
K+1 is the present iteration count
In Gauss method , updation of bus voltage is done only at the end of one full iteration .Latest values are not used by Gauss method .Therefore it takes too many iterations to converge .The solution time become prohibitally large . Thus Gauss method is not used in our load flow studies .

1.4 Gauss-Seidel Method(GS) :

Seidel has overcome the above disadvantage by updating the bus voltage immediately and always uses the latest bus voltage(E_P^{K+1}).

$$E_P^{K+1} = \frac{1}{Y_{PP}}\left[\frac{P_P - jQ_P}{E_P^{k*}} - \sum_{\substack{P \neq q \\ q=1}}^{p-1} Y_{pq} \, E_q^{k+1}\right] \quad (2)$$

Now calculate

$$\Delta E_P^{K+1} = E_P^{K+1} - E_P^{K} \qquad (3)$$

$$E_P^{K+1} = E_P^{K} + \alpha \Delta E_P^{K+1} \qquad (4)$$

α is called as acceleration factor

1.4.1 Significance of acceleration factor : The acceleration factor largely affects the convergence of the algorithm . It is found that the value of α between 1.4-1.7 gives the best voltage through iterations. The impact of various acceleration factors in GS is discussed below [6-13]:

$\alpha= 1$: No acceleration is used . So, takes more iteration to converge .

$\alpha= 1.2$: Little acceleration is used .A little bit improvement , convergence is observed.

$\alpha= 1.4-1.7$: Found to be best range to reduce number of iterations .It is best range by trial and error approach .

5 bus system : $\alpha= 1.4$: Converged in 10 iterations.

14 bus system : $\alpha= 1.55$: Converged in 17 iterations.

30 bus system : $\alpha= 1.6$: Converged in 28 iterations.

57 bus system : $\alpha= 1.55$: Converged in 58 iterations.

118 bus system : $\alpha= 1.7$: Converged in 97 iterations.

1040 bus system : $\alpha= 1.7$: Converged in 980 iterations.

$\alpha= 1.8$: Causes very big acceleration which leads to non-linearity and further it causes numerical divergence.

So, α is to be selected by us optimally for a given power system .

In GS-method number of iterations for convergence is proportional to size of the system. So, solution time will be very large for big power systems .Though, GS method is simple in nature ,it cannot be used for real time study of a big system.

1.4.2 PV-Bus treatment : At PQ bus P_P and Q_P are known. So equation(2) can be easily solved to get E_P^{K+1} .For slack bus all the values are referenced value. At PV bus Q_P is not known .It must be

$$Q_{min} \leq Q_P \leq Q_{max} \qquad (5)$$

Now calculation at PV bus or PV bus treatment is as follows :

At PV bus V_{sp} , Q_{min}, Q_{max}, Q_{load} are given

$Q_P = Q_{gen} - Q_{load} =$ Injected reactive power.

In PV bus treatment , we must enforce Q limit w.r.t $Q_{max,inj}$ and $Q_{min,inj}$ as we calculate Q_p as injection value .

Let $E_P^K = e_p^k + jf_p^k \qquad (6)$

$$\delta_p^k = \tan^{-1}\left(\frac{f_p^k}{e_p^k}\right) \qquad (7)$$

$$e_{new} = V_{SP}(P)\cos(\delta_P^K) \qquad (8)$$

$$f_{new} = V_{SP}(P)\sin(\delta_P^K) \qquad (9)$$

$$E_{new} = e_{new} + jf_{new} \qquad (10)$$

$$I_{new} = Y_{pp}E_{new} + \sum_{q \neq p}^{n} Y_{pq}E_q^{k+1} \qquad (11)$$

$$= Y_{pp}E_{new} + \sum_{q=1}^{p-1} Y_{pq}E_q^{k+1} + \sum_{q=p+1}^{n} Y_{pq}E_q^{k} \qquad (12)$$

Complex power injection

$$= E_{new}I_{new}^* \qquad (13)$$

$$Q_{new} = \text{Imaginary} (S_{new}) \qquad (14)$$

If $Q_{new} < Q_{min,inj} - Q_{new}$ is violating lower limit

If $Q_{new} > Q_{max,inj} - Q_{new}$ is crossing the upper limit

When

$Q_{min,inj} \leq Q_{new} \leq Q_{max,inj} - Q_{new}$ is within Q limits

Q_{min} and Q_{max} are called Hard limits and V_{max} and V_{min} are called soft limits .

In GS method we can enforce the Q limits, that comes under the category of Q-adjusted study . Q-unadjusted study is not possible in GS as in that case Q_{min} and Q_{max} have wide limits , so V_{sp} can easily maintained .

PV bus is supposed to maintain the specified voltage but when Q_{new} violates the lower limit or upper limit , it will be converted into PQ bus category . Where , the voltage is not allowed to vary as per load conditions .

When Q_{new} are within the limit , the PV bus is having the ability to maintain V_{sp} , and hence maintains the PV bus status.

1.4.3 Merits of the GS Method :

i)Very simple to understand .

ii)Easy to write full length program including sparsity aspect .

iii)It takes less time per iteration. In GS method linear convergence is observed .

iv)It needs very less memory .

v)Easy to enforce Q-limits at PV buses .

vi) Easy to simulate line outage or transformer outage.

In practical power system, a line get disconnected by opening of circuit breaker at both ends .Electrical disconnection means the impedance is infinity[6,7,13-16] .we put

$R(K) = 10^{20}$ p.u

$X(K) = 10^{20}$ p.u

$Y_{cp} = 0.0$

$Y_{cq} = 0.0$

and modify appropriate Y_{bus} locations and then run GS method .(Y_{cp}, Y_{cp} are shunt conductances).

vii) Easy to simulate generator outage.
(put $P_{gen}(i) = 0$ and $V_{sp}(i) = 1.0$

1.4.4 Demerits of the GS Method :

i)Number of iterations proportional to the size of the system .

5bus- 10 iterations
14 bus-17 iterations
30 bus -28 iterations
57 bus-56 iterations
118 bus-98 iterations
1040bus- 990 iterations

Total solution time is prohibitively large for large power system.GS is not useful for real time applications .We can make use of GS method to have better exposure and experience in load flow solution of power system if it is used for small systems as planning stage studies i.e off-line study .

ii)It demands good slack bus position (Centrally located big Generating station to be as slack bus).

iii)Acceleration factor is to be selected by trial and error for optimum value.

iv)It fails to converge on overload system, ill-condition system ,radial system.

1.5 NR load flow(NRLF) :
NR method is proposed by Tinney Peterson (1963). In NR method all buses is updated simultaneously. This become very strong point for good convergence for NR . In power system load flow solutions many of the other algorithms except NR , may failed to converge on ill-conditioned system (X/R ratio low) but NR method,exhibits good convergence (Quadratic convergence characteristics) in all types of power system even loading conditions are ill-conditioned. Thus we normally call NR as parent load flow algorithm[6-7].NR method can be described by the following equations :

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} H & N \\ M & L \end{bmatrix} \begin{bmatrix} \Delta \delta \\ \Delta V / V \end{bmatrix} \qquad (15)$$

1.5.1 Merits of NRLF :

i)NR exhibits quadratic convergence characteristics and converges within 3 iterations for a very high accuracy of 0.0001 p.u for ΔP_{max} and ΔQ_{max}.

ii) No. of iterations are independent of size of the system .

5 bus – 3 iterations
14 bus – 3 iterations
30 bus – 3 iterations
57 bus – 3 iterations
118 bus – 3 iterations
1040 bus- 3 iterations

iii) It converges on ill-conditioned systems , well conditioned system and overloaded power system.

iv)Easy to simulate line outages and generator outages.

v)Easy to enforce the Q limits .(i.e $Q_{adjusted}$ load flow is possible).

vi) NR is not affected by the location of slack bus position.

1.5.2 Demerits of NRLF :

i)Total CPU time is very large. To reduce the total CPU time , we need to use sparsity technique even for Jacobian elements. The modern practice is to use sparsity technique for jacobian of NRLF and make it as a potential algorithm for online load flow solution as well.

1.6 Advanced Newton's Decoupled (NDC) / Fast Decoupled(FDC) Load Flow Method :

Fast Decoupled method is proposed by Brain Stott in 1973 . It is an advanced version of NRLF

.So, it is called Newton's Decoupled method (NDC) also .Here weak coupling between M and N is assumed . So, it becomes as follows[6,7,13-16]:

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} H & 0 \\ 0 & L \end{bmatrix} \begin{bmatrix} \Delta \delta \\ \Delta V / V \end{bmatrix}$$

(16)

$$[\Delta P] = [H][\Delta \delta]$$

(17)

$$[\Delta Q] = [L]\left[\frac{\Delta V}{V}\right]$$

(18)

The above relations can be represented as

$$\left[\frac{\Delta P}{V}\right] = [B'][\Delta \delta]$$

(19)

$$\left[\frac{\Delta Q}{V}\right] = [B''][\Delta V]$$

(20)

The above equations(equn. 19 & 20) are called FDC equations .

1.6.1 Merits of FDC :

i)Two constant slope matrices (B', B'') are used in FDC .They need to be formed and decomposed only once .So, large CPU time reduction is observed .
ii)No. of iterations are independent of system size .
5 bus – 3.5 iterations (ϵ=0.0001p.u)

Q-unadjusted case:

14 bus -4.5 iterations
30 bus-4 iterations
57 bus-4.5 iterations
118 bus- 4.5 iterations
1040 bus -4.5 iterations

For Q-adjusted case, another 2-3 iterations are required (6-7.5 iterations).

iii)Total solution CPU time is low .It is very widely used in real time studies.
Any learner should attempt GS method first , then directly FDC and if failed , then should attempt by NR method for load flow solutions .
iv) Sparsity technique can be used easily for B', B'' formation and also for decomposition.

v) No special guess voltages are required . Flat start (V= 1+j0) is o.k .

1.6.2 Demerits of FDC :

i) Enforcement of Q-limit is very difficult .
ii)Line outage simulation will change the structure of B' and B'' . They need to be reformed and retriangularised .

1.7 Best Suitable Method for our Work :

FDC exhibits Geometric convergence characteristics .It takes less memory (50% of NR) and total solution CPU time is also very low . But it may exhibit slow convergence or in some cases fail to converge on ill-condition system .Proper selection of slack bus position is required for FDC method. In other words, convergence of FDC is influenced by the location of slack bus but it is not in case of NR .So, NR is the best method among iterative techniques of load flow study.

In our work , we have used Power World 12.0 commercial version to create IEEE 57 , IEEE 118 and IEEE 300 Bus system and run NRLF to find relatively weak voltage profile buses in that Wide area systems. Then we placed capacitor of different compensations between weakest buses and again run NRLF. The we find the impact of the capacitor in whole network in terms of sending end voltage , receiving end voltage , active power and reactive power . We compared the results with before and after compensation cases.

2.GENERAL VIEW ABOUT POWER WORLD SIMULATOR

Power world simulator is an interactive power system simulation package designed to simulate high voltage power system operation on a time frame ranging from several minutes to several days. The software contains a highly effective power flow analysis package capable of efficiently solving systems of up to 250,000 buses. Power world software is capable of doing load flow study , contingency analysis , fault analysis , sensitivity analysis ,optimal power flow analysis etc of network.

3.DIFFERENT VOLTAGE LEVELS AND PERMISSIBLE VOLTAGE FLUCTUATIONS

The voltages are classified into following levels as per IEC (International Electro-technical commission)[4-16].e.g.-
1)Low Voltage – up to 1000 volts only.
2) Medium Voltage – 1KV to 33 KV.
3) High Voltage – 33 KV to 245 KV
4) Extra High Voltage – above 245 KV
5) Ultra High Voltage – above 800 KV
As per Indian Electricity Rules , except with the written consent of the consumer or previous sanction of the state Government a supplier shall not permit the voltage at the point of commencement of the supply as defined under rule 58 to vary from the declared voltage as follows[5] :
i)In case of low or medium voltage by more than 6%.
ii) In the case of high voltage, by more than 6 per cent on the higher side or by more than 9 per cent on the lower side.
iii)In the case of extra high voltage, by more than 10 per cent on the higher side or by more than 12.5 per cent on the lower side.

So, in any test system voltage goes beyond lower or upper limit is a threat for power system. Our work is an effort to maintain a good voltage profile and improved power transfer capability of Wide area power systems.

4.SIMULATED TEST SYSTEMS

In Power World Simulator 12.0 commercial version we have created IEEE 57 , IEEE 118 and IEEE 300 bus test system and then run NRLF to find weakest bus and strongest bus . Then we placed capacitors with different compensations between weak profile buses and observed their impact on the network . Fig 1 is showing constructed IEEE 57 bus test system by using power world software. Fig 2 is showing constructed IEEE 118 bus test system by using power world software . Fig 3 is showing constructed IEEE 300 bus test system by using power world software .
We got the relevant data for construction from reference [9].
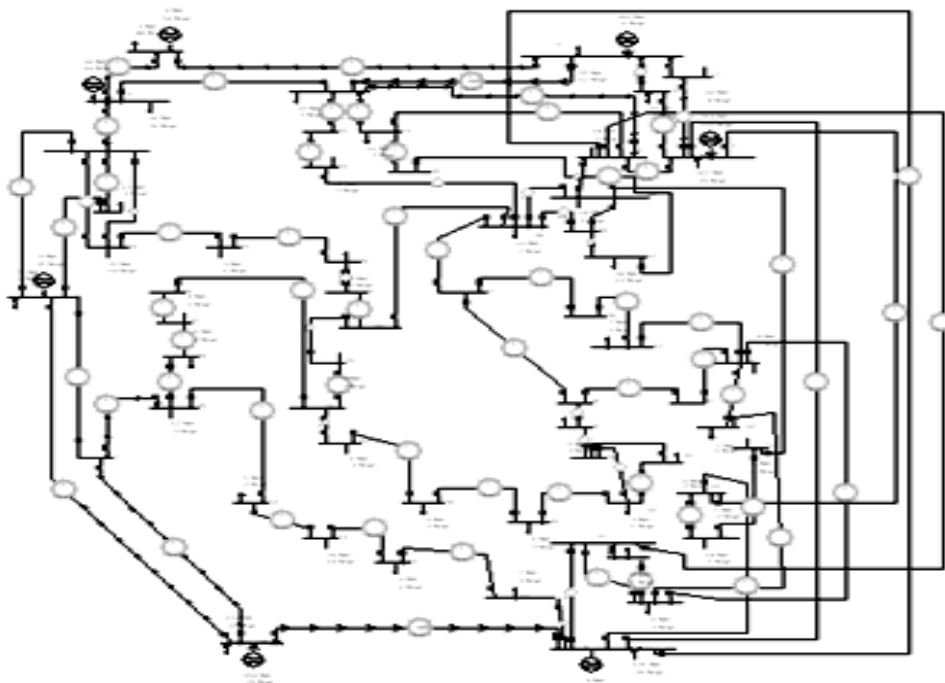

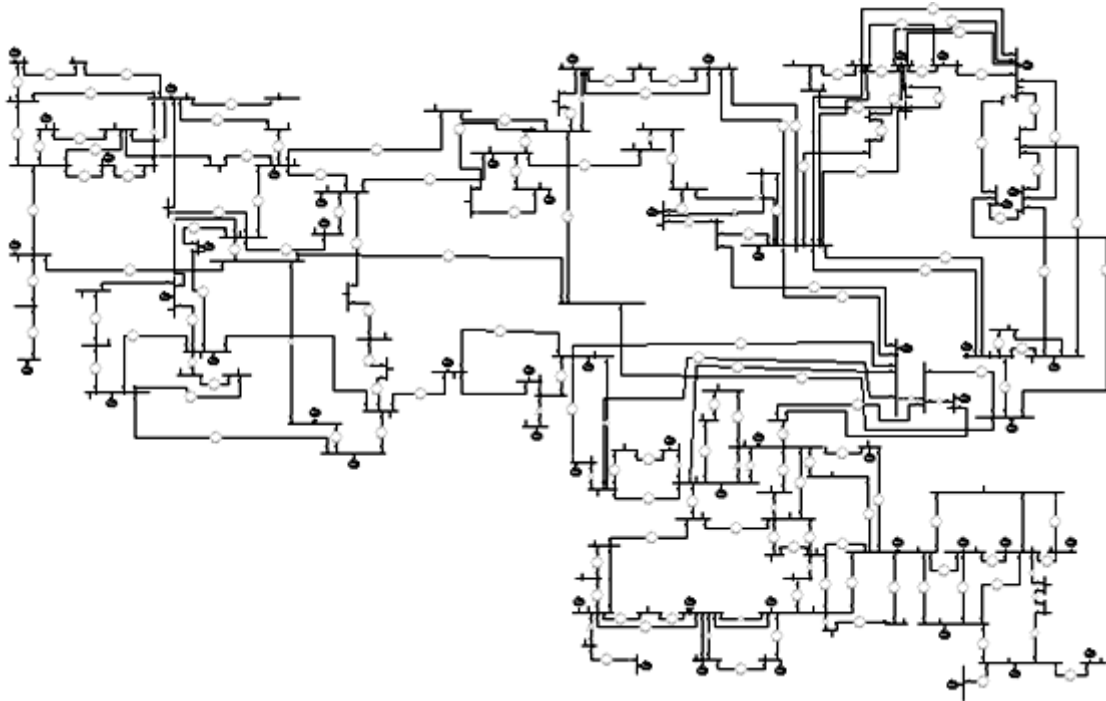Fig 1 :IEEE 57 Bus Test System in Power World Software(Top View)

Fig 2 : IEEE 118 Bus Test System in Power World Software(Top View)
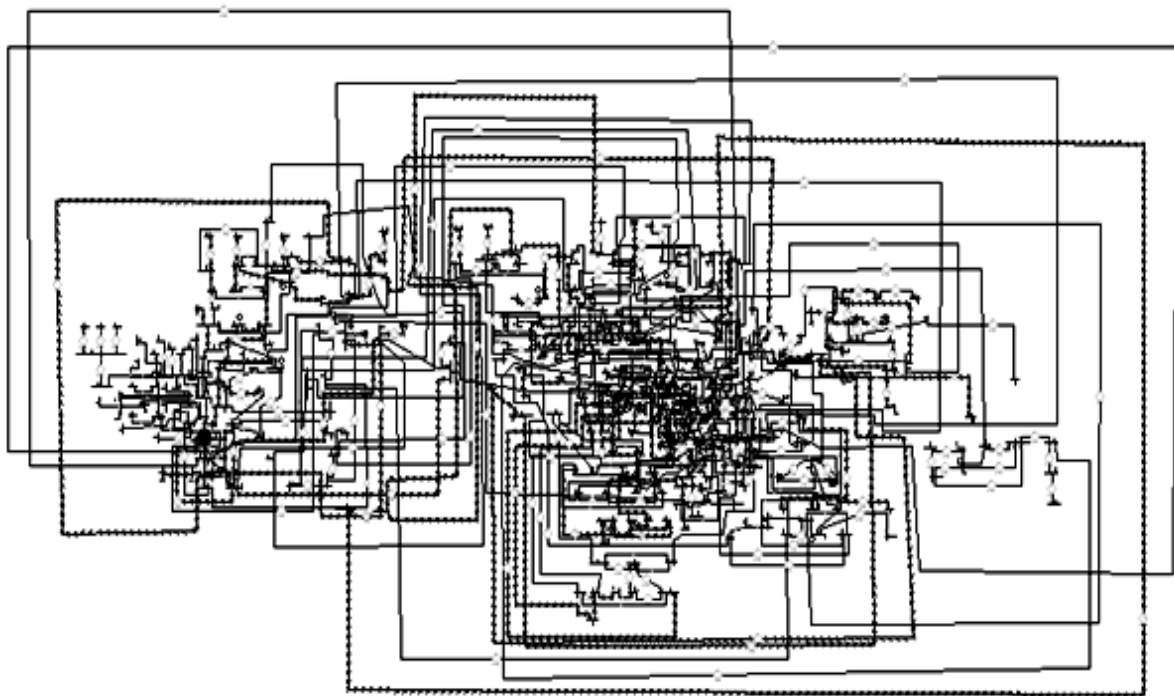
Fig 3 :IEEE 300 Bus Test System in Power World Software(Top View)

5. RESULTS

After running NRLF to IEEE 57 Bus system we got Bus 51 is strongest bus having p.u bus voltage 1.01748 p.u and Bus 46 is 2nd strongest bus having p.u voltage 1.01098 p.u. After running the NRLF , we found 10 buses below 0.9 p.u.

Which we termed as weak bus or weak voltage bus. The weakest bus we got at Bus no. 31(voltage 0.80779 p.u) and second weakest bus we got at Bus no. 30 (voltage 0.81367 p.u).

We placed capacitor between bus 30 and bus 31 and run the NRLF again and listed values of corresponding bus voltages with 10% , 20% ,30% and 40% compensation.

We listed all the corresponding bus voltages (initially considered as weak buses) after placing capacitor in Table –I and observed the Changes From Table-I, it is clear that after inserting series capacitor in line between bus 30 and bus 31, the voltage profile also changes

Voltage profile improves towards receiving end and it slightly decreases towards sending end . With the increase of series compensation this effect gradually increases i.e. receiving end voltages gradually increase and sending end voltage gradually decreases . This incident resembles network's Ferranti effect phenomena . We considered up to 40% series compensation because beyond this value may affect network's stability..

Table- I Weak Voltage Profile buses of IEEE 57 Bus system (without compensation) : impact on bus voltages after implementing series compensation between bus 30 and bus 31

Bus No.	p.u volt				
	Without compensation	10% compensation	20% compensation	30% compensation	40% compensation
25	0.82652	0.82595	0.82534	0.82472	0.82407
26	0.89969	0.89963	0.89957	0.89950	0.89943
30	0.81367	0.81303	0.81234	0.81166	0.81094
31	0.80779	0.80813	0.80845	0.80880	0.80917
32	0.86481	0.86490	0.86498	0.86507	0.86517
33	0.86884	0.86892	0.86900	0.86908	0.86916
34	0.86884	0.86892	0.86900	0.86908	0.86916
35	0.88058	0.88064	0.88069	0.88075	0.88081
36	0.89445	0.89449	0.89453	0.89457	0.89461
40	0.89260	0.89265	0.89268	0.89272	0.89277

Table- II Transmission lines between weak Voltage Profile buses of IEEE 57 Bus system (without compensation) : impact on active and reactive power flow after implementing series compensation between bus 30 and bus 31

From bus	To bus	Active and Reactive Power Flow among Transmission Lines									
		Without compensation		10% Compensation		20% Compensation		30% Compensation		40% Compensation	
		MW	MVAR	MW	MVAR	MW	MVAR	MW	MVAR	MW	MVAR
25	30	2.4	3.7	2.4	3.7	2.3	3.7	2.3	3.8	2.3	3.8
26	27	-8.6	-9.6	-8.6	-9.6	-8.6	-9.6	-8.6	-9.7	-8.6	-9.7
24	25	8.7	9.0	8.7	9.0	8.6	9.1	8.6	9.1	8.6	9.2
30	31	-1.3	1.8	-1.3	1.8	-1.3	1.9	-1.3	1.9	-1.3	1.9
31	32	-7.1	-1.1	-7.1	-1.1	-7.1	-1.0	-7.1	-1.0	-7.1	-1.0
32	33	-8.1	-0.8	-8.8	-0.1	-8.8	-0.1	-8.8	0	-8.8	0
33	34	-12.7	-2.1	-12.6	-2.0	-12.6	-2.0	-12.6	-2.0	-12.6	-1.9
34	32	0.3	2.5	0.3	2.5	0.3	2.5	0.3	2.5	0.3	2.5
34	35	-12.9	-4.5	-12.9	-4.5	-13.0	-4.5	-13.0	-4.4	-13.0	-4.4
35	36	-19.1	-7.5	-19.1	-7.4	-19.1	-7.4	-19.1	-7.4	-19.1	-7.3
36	37	-21.5	-9.7	-21.5	-9.7	-21.5	-9.7	-21.5	-9.7	-21.6	-9.6
36	40	2.2	2.1	2.2	2.1	2.2	2.1	2.2	2.1	2.2	2.1
40	56	2.2	2.1	2.2	2.1	2.2	2.1	2.2	2.1	2.2	2.1

Table –III : Strong and Weak Buses of IEEE 118 and IEEE 300 Bus system

Test System	Strong Buses		Weak Buses	
	Bus No.	Bus Voltage (p.u)	Bus No.	Bus Voltage (p.u)
IEEE 118 Bus	10	1.05	53	0.94404
	25	1.05	63	0.94963
	65	1.05	76	0.94300
	66	1.05	118	0.94826
IEEE 300 Bus	1	3.48586	43	1.03408
	22	3.53707	44	1.84137
	140	3.95060	257	1.03408
	141	4.04742	266	2.18921
	144	4.22221	288	2.19425

From the above Table-II, it is clear, after inserting series capacitor reactive power deficit in the circuit improves . The negative MVAr tends to go towards zero. Active power transfer capability is also improved. Table-III describes strong and weak buses of IEEE 118 Bus and IEEE 300 Bus systems. IEEE 118 Bus system obeys the Indian Electricity Rules of voltage fluctuations and all the p.u voltage values are within permissible range of high voltage . IEEE 300 bus systems results are more fluctuating . But with the use of series capacitor, the volage profile can be improved similar to IEEE 57 bus system.

6.CONCLUSION

Based on the review , it can be said that the strength of the bus can be determined from its voltage profile after running the load flow . And in this context application of NRLF is the best solution. Voltage profile , active power transfer capability improvement and mitigation of scarcity of reactive power in the power network can be done by inserting series capacitor in the circuit. The review of the paper has given an insight about strongest and weakest bus of the system ,most suitable algorithm for the solution of load flow problem, different problems faced by power systems due to weak voltage profile and scarcity of reactive power in the network and their solution for a better voltage – reactive power balance for a reliable and secured operation of wide area power systems.

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