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Improvement of Voltage Stability in Multi-Bus Power System by Network Reconfiguration Approach

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Abstract: **Due to economic reasons arising out of deregulation and open market of electricity, modern day power systems are being operated closer to their stability limits. Voltage stability problems have been one of the major concerns for electric utilities as a result of heavier loading of power systems. Maintaining voltage stability & specified voltage levels at all nodes in a large & heavily loaded Power network is a critical & challenging task for power engineers. A number of different approaches have been reported in papers for improvement of voltage stability. In this paper a method for improving voltage stability in a power network comprising of multiple lines & switches has been suggested based on Network Reconfiguration approach. Network Reconfiguration is intended to enhance the voltage stability by determination of switching options that maximize voltage stability the most for a particular set of loads and is performed by altering the topological structure of the system. In this paper reconfiguration of a power network is achieved by addition of new power lines to the existing network. Attempt has been made to find out the best possible combination of switches & lines, which results in highest voltage stability of the overall system. The present work reveals that careful and optimum selection of power lines and inter connection switches can provide the best voltage stability solution for a given loading condition. The proposed Reconfiguration method is applied to the standard IEEE-14 Bus test system. The IEEE-14 Bus SYSTEM is reconfigured by addition of four power lines.**

Keywords: Voltage Stability, Network Reconfiguration, L-index, Loss minimization.

I. INTRODUCTION

Voltage control and stability problems are now receiving special attention in highly developed networks as a result of heavier loading. Due to fast growth in power demand incidence of sudden voltage collapse has been experienced. When such an incident happens, some industrial loads will be switched off through automatic cut-off switches, resulting in severe interruptions. The phenomenon of voltage collapse has been observed in many countries and has been analyzed extensively in recent years. Most of the incidents of voltage collapse are related to heavily stressed power systems where large amounts of real and reactive power are transported over long extra high voltage (EHV) transmission lines, while appropriate reactive power sources are not available to maintain normal voltage profiles at receiving end buses. Most EHV transmission lines being very sensitive to real and reactive power changes, frequently suffers from voltage instability [1-3]. Improvement of voltage stability is very much essential in order to ensure desired power transfer at rated voltage "Voltage stability concerned with the ability of power system to maintain the acceptable voltages at all system buses under normal conditions as well as when the system is being subjected to a disturbance". Voltage stability is classified into large-disturbance voltage stability and small disturbance voltage stability [4]. The former is concerned with a system's ability to control voltages following large disturbances such as system faults, loss of generation, or circuit contingencies. The latter concerned with a system's ability to control voltages following small perturbations such as incremental changes in system load. The basic processes contributing to small-disturbance voltage instability are essentially of a steady-state nature. Therefore, static analysis can be effectively used to determine stability margins which show how close current operating point of a power system is to the voltage collapse point. Recently, a large number of papers have addressed the issue of quantifying the distance of a specific operating state to voltage collapse point.

This paper uses the voltage stability index for stressed power system has been derived by Jasmon and Lee [4] from a reduced system model, and this index could identify how far a system is from its point of collapse. A new relationship between voltage stability and power losses has been proposed to show that voltage stability is improved when power losses are reduced [5]. Network reconfiguration approach has then been used to improve the overall voltage stability of the system.

Network reconfiguration can be used as a real-time control tool in power system operation and planning. Network reconfiguration alters the topological structure of the network. In the present paper power network is reconfigured by addition of power lines between the buses. From time to time the power network is reconfigured by changing the ON/OFF status of additional power lines so that, the voltage stability is maximized for a given loading condition. In case of distribution networks, sectionalizing-switches and tie-switches are used. These switches can be used for both protection and network reconfiguration. Modifying radial structure of the feeders by changing the ON/OFF status of sectionalizing and tie-switches to transfer loads from one feeder to another may significantly improve the operating conditions of the overall system.

LOAD FLOW

The modern approach of power system is interconnections of all the generating stations i.e. forming a grid system. Load demand undergoes wide changes in the day. The generation of power at all the moments should be equal to the demand. One of the advantages of grid system is generation of power always meet the load demand at all times. For most economic operation the load must be shared in equal ratios. Care must be taken so that none of interconnected station may be overloaded. Newton-Raphson method is based on Taylor's series and partial derivatives. The N-R method is recent, take less computer time hence computation cost is less and the convergence is certain. The Newton-Raphson method is more accurate, and is insensitive to factors like slack bus selection, regulating transformers etc. and the number of iterations required in this method is almost independent of the system size. So using Newton-Raphson Load flow Method of the IEEE-14 BUS SYSTEM having bus data and line data. So the load flow result is shown in table-3 by using mat lab software

Bus No.	Bus Voltages		Load Data		Generator Data				Static MVar
	Magnitude	Degree	MW	MVar	MW	MVar	Qmin	Qmax	+Qc/-Qc
1	1.060	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2	1.045	0.0	21.7	12.7	40.0	0.0	-40.0	50.0	0.0
3	1.010	0.0	94.2	19.0	0.0	0.0	0.0	40.0	0.0
4	1.000	0.0	47.8	-3.9	0.0	0.0	0.0	0.0	0.0
5	1.000	0.0	7.6	1.6	0.0	0.0	0.0	0.0	0.0
6	1.070	0.0	11.2	7.5	0.0	0.0	-6.0	24.0	0.0
7	1.000	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
8	1.090	0.0	0.0	0.0	0.0	0.0	-6.0	24.0	0.0
9	1.000	0.0	29.5	16.6	0.0	0.0	0.0	0.0	19.0
10	1.000	0.0	9.0	5.8	0.0	0.0	0.0	0.0	0.0
11	1.000	0.0	3.5	1.8	0.0	0.0	0.0	0.0	0.0
12	1.000	0.0	6.1	1.6	0.0	0.0	0.0	0.0	0.0
13	1.000	0.0	3.5	5.8	0.0	0.0	0.0	0.0	0.0
14	1.000	0.0	14.9	5.0	0.0	0.0	0.0	0.0	0.0

TABLE-1: Us-Data for the IEEE-14 Bus System

Lines	Starting Bus	End Bus	R (p.u)	X (p.u)	B/2 (p.u)	Tap setting Value
L1	1	2	0.01938	0.05917	0.02640	1
L2	1	5	0.05403	0.22304	0.02460	1
L3	2	3	0.04699	0.19797	0.02190	1
L4	2	4	0.05811	0.17632	0.01870	1
L5	2	5	0.05695	0.17388	0.01700	1
L6	3	4	0.06701	0.17103	0.01730	1
L7	4	5	0.01335	0.04211	0.0064	1
L8	4	7	0.00000	0.20912	0.0000	0.978
L9	4	9	0.00000	0.55618	0.0000	0.969
L10	5	6	0.00000	0.25202	0.0000	0.932
L11	6	11	0.09498	0.19890	0.0000	1
L12	6	12	0.12291	0.25581	0.0000	1
L13	6	13	0.06615	0.13027	0.0000	1
L14	7	8	0.00000	0.17615	0.0000	1
L15	7	9	0.00000	0.11001	0.0000	1
L16	9	10	0.03181	0.08450	0.0000	1
L17	9	14	0.12711	0.27038	0.0000	1
L18	10	11	0.08205	0.19207	0.0000	1
L19	12	13	0.22092	0.19988	0.0000	1
L20	13	14	0.17093	0.34802	0.0000	1

TABLE-2: Line-Data for the Ieee-14 Bus System

Bus No.	Voltage Mag.	Angle Degree	Load MW	Mvar	Generation MW	Mvar	Injected Mvar
1	1.060	0.000	0.000	0.000	232.314	-16.794	0.000
2	1.045	-4.981	21.700	12.700	40.000	42.660	0.000
3	1.010	-12.719	94.200	19.000	0.000	23.568	0.000
4	1.018	-10.318	47.800	-3.900	0.000	0.000	0.000
5	1.020	-8.781	7.600	1.600	0.000	0.000	0.000
6	1.070	-14.242	11.200	7.500	0.000	13.070	0.000
7	1.061	-13.357	0.000	0.000	0.000	0.000	0.000
8	1.090	-13.357	0.000	0.000	0.000	18.023	0.000
9	1.054	-14.935	29.500	16.600	0.000	0.000	19.000
10	1.049	-15.098	9.000	5.800	0.000	0.000	0.000
11	1.056	-14.800	3.500	1.800	0.000	0.000	0.000
12	1.055	-15.096	6.100	1.600	0.000	0.000	0.000
13	1.050	-15.174	13.500	5.800	0.000	0.000	0.000
14	1.034	-16.041	14.900	5.000	0.000	0.000	0.000
		Total	**259.000**	**73.50**	**272.314**	**80.527**	**19.000**

TABLE-3: Load flow result for IEEE-14 Bus system.

II. COMPUTATION OF VOLTAGE STABILITY INDEX FOR A REDUCED SINGLE-LINE EQUIVALENT NETWORK

Consider the single-line system shown in Fig.1.
Let,

P = injected real power
Q = injected reactive power

V= sending end voltage
r = resistance of the line
x = reactance of line
Q_l = reactive load
P_l = real load

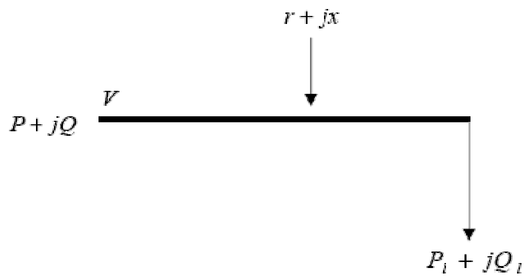

Fig. 1 Single-line system

From the Fig. 1, the real and reactive power equations can be derived as

$$P = \frac{r(P^2 + Q^2)}{V^2} + P_l \qquad (1)$$

$$Q = \frac{x(P^2 + Q^2)}{V^2} + Q_l \qquad (2)$$

From equations (1) & (2), we can eliminate $\frac{r(P^2 + Q^2)}{V^2}$ terms by rearranging the equations and obtain,

$$x(P - P_l) = r(Q - Q_l) \qquad (3)$$

The voltage at sending is the reference voltage, and its magnitude is kept constant. Hence, the sending end voltage is assumed as 1 per unit. On rearranging equation (3) and eliminating Q from equation (1), a quadratic equation in P is obtained as

$$(r^2 + x^2)P^2 - (2x^2P_l - 2rxQ_l)P + (x^2P_l^2 + r^2Q_l^2 - 2rxP_lQ_l + rP_l) = 0 \qquad (4)$$

And eliminating P from equation (1), a quadratic equation in Q is obtained as

$$(r^2 + x^2)Q^2 - (2x^2Q_l - 2rxP_l)Q + (x^2P_l^2 + r^2Q_l^2 - 2rxP_lQ_l + rQ_l) = 0 \qquad (5)$$

As equations (4) and (5) are in quadratic form, for P and Q to have real roots, the determinants of equations (4) and (5), respectively, must be greater than or equal to zero. Thus,

$$(2x^2P_l - 2rxQ_l + r)^2 - 4(r^2 + x^2)(x^2P_l^2 + r^2Q_l^2 - 2rxP_lQ_l + rP_l) \geq 0 \qquad (6)$$

$$(2x^2Q_l - 2rxP_l + x)^2 - 4(r^2 + x^2)(x^2P_l^2 + r^2Q_l^2 - 2rxP_lQ_l + xQ_l) \geq 0 \qquad (7)$$

Simplifying equation (6) or (7), we obtain

$$4[(xP_1 - rQ_1)^2 + xQ_1 + rP_1] \leq 1 \quad (8)$$

For a given power network, the total real and reactive power can be computed as

$$P = \sum P_{loss} + \sum P_{li} \quad (9)$$

$$Q = \sum Q_{loss} + \sum Q_{li} \quad (10)$$

Where $\sum P_{loss}$ and $\sum Q_{loss}$ are the total real and reactive power losses in the system and $\sum P_{li}$ & $\sum Q_{li}$ are the total real and reactive loads, respectively.

A real power network consisting of many lines can be reduced to a system with only one line. It has been shown that by applying the single-line method for the reduction of network, the occurrence of voltage collapse can be studied easily, and it is not necessary to consider every line of the network separately. By using the single-line method, the total real and reactive powers can be found as

$$P = r_{eq}(P^2 + Q^2) + \sum P_{li} \quad (11)$$

$$Q = x_{eq}(P^2 + Q^2) + \sum Q_{li} \quad (12)$$

Where r_{eq} and x_{eq} are the equivalent resistance and reactance, respectively, in the single line. Recalling equation (8), the stability index L can be defined as

$$L = 4[(xP_1 - rQ_1)^2 + xQ_1 + rP_1] \quad (13)$$

Hence, for a reduced single-line network, equation (13) can be rewritten as

$$L = 4[(x_{eq}P_{leq} - r_{eq}Q_{leq})^2 + x_{eq}Q_{leq} + r_{eq}P_{leq}] \quad (14)$$

Where P_{leq} and Q_{leq} are the total real and reactive loads, respectively, in the distribution network. From equations (9) to (12), the equivalent resistance and reactance of a reduced single line network can be defined as

$$r_{eq} = \frac{\sum P_{loss}}{\{(P_{leq} + \sum P_{loss})^2 + (Q_{leq} + \sum Q_{loss})^2\}} \quad (15)$$

$$x_{eq} = \frac{\sum Q_{loss}}{\{(P_{leq} + \sum P_{loss})^2 + (Q_{leq} + \sum Q_{loss})^2\}} \quad (16)$$

For a stable system, the value of stability index, L is very much less than 1; however, if the value of L approaches 1, this would indicate that the system is close to voltage collapse. If the network is loaded beyond this critical limit, the power becomes imaginary, and it is at this point that the voltage collapse occurs.

Relationship between Voltage Stability and Power Loss

Substitute the values of r_{eq} and x_{eq} from equations (15) and (16) into the voltage stability of equation (14), the stability index becomes

$$L=4\left[\begin{aligned}&\left\{\frac{\left(\sum Q_{loss}\right)P_{leq}}{\left(P_{leq}+\sum P_{loss}\right)^2+\left(Q_{leq}+\sum Q_{loss}\right)^2}-\frac{\left(\sum P_{loss}\right)Q_{leq}}{\left(P_{leq}+\sum P_{loss}\right)^2+\left(Q_{leq}+\sum Q_{loss}\right)^2}\right\}^2\\&+\frac{\left(\sum Q_{loss}\right)Q_{leq}}{\left(P_{leq}+\sum P_{loss}\right)^2+\left(Q_{leq}+\sum Q_{loss}\right)^2}+\frac{\left(\sum P_{loss}\right)P_{leq}}{\left(P_{leq}+\sum P_{loss}\right)^2+\left(Q_{leq}+\sum Q_{loss}\right)^2}\end{aligned}\right] \quad (17)$$

By assuming that $P_{leq} >> \sum P_{loss}$ and $Q_{leq} >> \sum Q_{loss}$, the simplified stability index L can be obtained as follows

$$L=4\left[\begin{aligned}&\left\{\frac{\left(\sum Q_{loss}\right)P_{leq}}{\left(P_{leq}\right)^2+\left(Q_{leq}\right)^2}-\frac{\left(\sum P_{loss}\right)Q_{leq}}{\left(P_{leq}\right)^2+\left(Q_{leq}\right)^2}\right\}^2\\&+\frac{\left(\sum Q_{loss}\right)Q_{leq}}{\left(P_{leq}\right)^2+\left(Q_{leq}\right)^2}+\frac{\left(\sum P_{loss}\right)P_{leq}}{\left(P_{leq}\right)^2+\left(Q_{leq}\right)^2}\end{aligned}\right] \quad (18)$$

By making $S_{leq}=\left|P_{leq}+jQ_{leq}\right|$, the simplified stability index L becomes,

$$L=\frac{4}{{S_{leq}}^2}\left[\begin{aligned}&\frac{1}{{S_{leq}}^2}\left\{\sum Q_{loss}\left(P_{leq}\right)-\left(\sum P_{loss}\right)Q_{leq}\right\}^2\\&+\left(\sum Q_{loss}\right)Q_{leq}+\left(P_{loss}\right)P_{leq}\end{aligned}\right] \quad (19)$$

The quadratic term $\left[\left\{\left(\sum Q_{loss}\right)P_{leq}-\left(\sum P_{loss}\right)Q_{leq}\right\}\Big/S_{leq}\right]^2$

in equation (19) is always positive and its value is very small as compared to other terms of the equation. From equation (19), it is seen that the stability index L increases with increase in power loss. On the other hand, if power loss is minimized, the stability value L is decreased and hence voltage stability improved.

III. NETWORK RECONFIGURATION TECHNIQUE

Network reconfiguration means restructuring the power lines which connect various buses in a power system. Restructuring of specific lines lead to alternative system configurations. Network reconfiguration can be accomplished by placing line interconnection switches into network. Opening and closing a switch connects or disconnect a line to the existing network. If there are N switches in a network, there are 2^N possible switching combinations. In this paper an IEEE-14 bus system is reconfigured by addition of four power lines. For 4 switches there will be 16 switching combinations. Improving voltage stability by network reconfiguration involve study of these 16 switching options and to identify optimum system configuration that will enhance voltage stability the most under a given loading and generation condition .The improvement of voltage stability is achieved only by altering topological structure of the power lines and does not involve any additional hardware like installation of SVC, capacitor bank, tap-changing transformers etc.. The challenge in the proposed method however lies with the task of finding the optimum switching pattern that would maximize the overall voltage stability of the system. Benefits of network reconfiguration are as follows:

a. Network reconfiguration improves the voltage stability of the system.
b. Network reconfiguration reduces the power losses and improves the reliability of power supply by changing the status of switches.
c. Network reconfiguration also helps smoothening out the peak demands, improving the voltage profile in the feeders and increase network reliability.
d. Enhancement of voltage stability can be achieved without any additional cost involved for installation of capacitors, tap changing transformers and the related switching equipment.

A. Enhancement of Voltage Stability by Network Reconfiguration involves following computational steps

1. Standard Load flow analysis program is used to obtain the values of bus voltages and complex powers.

2. $r_{eq} = \dfrac{\sum P_{loss}}{\{(P_{leq} + \sum P_{loss})^2 + (Q_{leq} + \sum Q_{loss})^2\}}$ and $x_{eq} = \dfrac{\sum Q_{loss}}{\{(P_{leq} + \sum P_{loss})^2 + (Q_{leq} + \sum Q_{loss})^2\}}$

   are estimated from the load flow analysis results.

3. With these values of r_{req} and x_{req}, the value of

   $L = 4[(x_{eq} P_{leq} - r_{eq} Q_{leq})^2 + x_{eq} Q_{leq} + r_{eq} P_{leq}]$ is computed.
4. L-Index for each switching combination is estimated separately.
5. The switching combination which gives the lowest value of L, i.e. the best voltage stability is determined.

IV. Case Studies And Results

A case study has been conducted on a modified IEEE-14 bus system. The standard IEEE-14 bus system has been modified with the addition of power lines which connect various buses in a power system by connection/disconnection switches. Also connection / disconnection switches have been placed in series with the existing lines. The system under study is illustrated in fig 2. By closing or opening a switch, a line can be added or removed from the system respectievely.’0’indicate switch is open,’1’ indicate switch is closed.

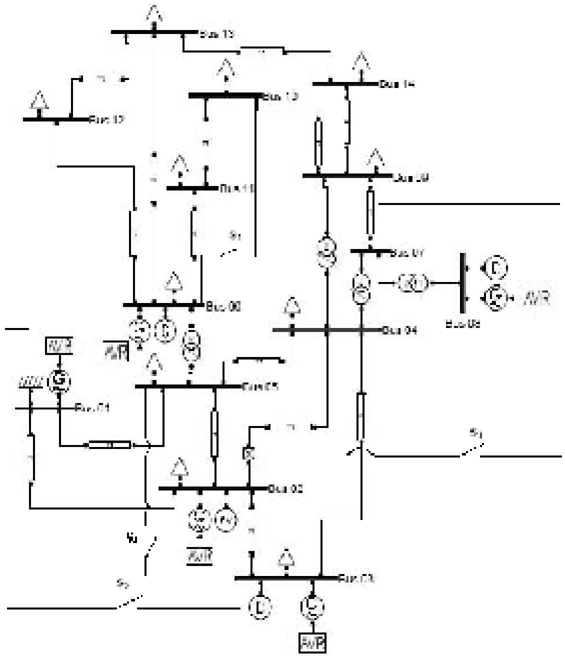

Fig. 2 Modified IEEE-14 Bus test system

'S': Switches which connected or disconnected additional power lines to the system.

A. Proposed Reconfiguration Scheme

Reconfiguration has been achieved by addition four power lines to the existing network. The number of additional lines has been restricted to four from the point of view of economic considerations as increasing the number of lines increases cost. The data for the additional lines are given in the following table 1.

Lines	Starting Bus	End Bus	R (p.u)	X (p.u)	B/2 (p.u)	Tap setting Value
L_1	7	2	0.00000	0.17615	0.00000	1
L_2	10	6	0.08205	0.19207	0.00000	1
L_3	12	3	0.12291	0.25581	0.00000	1
L_4	5	3	0.05403	0.22304	0.02460	1

TABLE 4: Line-Data for The New Lines Added to the Original IEEE-14 Bus System

V. DISCUSSION OF THE RESULTS

As discussed earlier, addition of four switches create 16 possible switching combinations and hence 16 different system configurations represented by system configuration codes 0-15 in table. 2. In the present work each of the 16 configurations has been studied separately and individually under any given loading condition. Four different states of bus loading have been considered.

Normal loading: All load buses have normal (100%) loading.
Load-1: 70% increase in load at 10-Bus & 30% decrease in load at 5, 14 Buses.
Load-2: 70% increase at 10-Bus & 30% decrease at 5, 14 & 70% increase in load at 13 bus.
Load-3: 90% increases in load at 9, 5Buses.
Value of L-index has been computed for each system configuration and for each individual loading condition. The computed values of L-index are presented in table 2.

System configuration No.	New lines added to the network ('0' indicates switch open, '1' indicate switch closed).				Computed L-index for the reduced single-line network under fixed loading and with different loading conditions			
	7-2 S_1	10-6 S_2	12-3 S_3	5-3 S_4	Normal Load Condition	Load-1	Load-2	Load-3
0	0	0	0	0	0.2758	0.2776	0.3067	0.3737
1	0	0	0	1	0.2426	0.2438	0.2739	0.3428
2	0	0	1	0	0.2847	0.2867	0.3200	0.3610
3	0	0	1	1	0.2523	0.2537	0.2838	0.3496
4	0	1	0	0	0.2740	0.2746	0.3066	0.3694
5	0	1	0	1	0.2411	0.2412	0.2738	0.3386
6	0	1	1	0	0.2832	0.2840	0.3176	0.3772
7	0	1	1	1	0.2511	0.2514	0.2816	0.3459
8	1	0	0	0	0.2258	0.2261	0.2513	0.2966
9	1	0	0	1	0.1903	0.1898	**0.2159**	**0.2622**
10	1	0	1	0	0.2321	0.2324	0.2601	0.3032
11	1	0	1	1	0.1942	0.1937	0.2201	0.2695
12	1	1	0	0	0.2254	0.2252	0.2521	0.2983
13	1	1	0	1	**0.1899**	**0.1890**	0.2163	0.2637
14	1	1	1	0	0.2316	0.2315	0.2592	0.3028
15	1	1	1	1	0.1938	0.1930	0.2199	0.2686

TABLE 5: Few Samples of the Computed L-Index Values For Normal and Modified System Configurations with Fixed Loading and Variable Load Condition

The computed L-index value for normal system configuration (configuration no: 0), as observed from the table: 2 is 0.2758. Many alternative system configurations result lower value of L-index compared to the normal configuration, and hence can improve overall voltage stability. With simultaneous addition of power lines (S_1=1, S_2=1, S_3=0, S_4=1) the L-index value is reduced to 0.1899. With variation of load, the optimum switching combination also changes. The variation in the value of L-index with change in system configuration is plotted in Fig. 3-6. The power losses in the system are also computed for each individual configuration and under all four different loading conditions. The power losses in the system before and after reconfiguration are shown in table 3.

Different loads	Losses before Reconfiguration		L-index for reduced single-line equivalent system before Reconfiguration	Losses after Reconfiguration		L-index For reduced single –line equivalent system after Reconfiguration.
	P (MW)	Q(Mvar)	L-index	P(MW)	Q(Mvar)	
Normal load	13.393	26.261	0.2758	10.870	12.493	0.1899
Load-1	13.600	26.489	0.2776	10.749	12.447	0.1890
Load-2	14.549	32.311	0.3067	11.854	17.569	0.2159
Load-3	17.717	47.376	0.3737	13.876	28.341	0.2622

TABLE-6: Power Losses before and after Reconfiguration

Best switching combinations for a given load and the corresponding L-index values are mentioned below:

a) Under normal load condition best combination is: S_1=1, S_2=1, S_3=0, S_4=1 (L-index: 0.1899).
b) Under load-1 condition best combination is: S_1=1, S_2=1, S_3=0, S_4=1 (L-index: 0.1890).
c) Under load-2 condition best combination is: S_1=1, S_2=0, S_3=0, S_4=1 (L-index: 0.2159).
d) Under load-3 condition best combination is: S_1=1, S_2=0, S_3=0, S_4=1 (L-index: 0.2622).

From the above results it is clear that with the variation of loads results in the change of switching combinations to obtain the best voltage stability. There exist a unique system configuration for each loading condition which would result in best voltage stability and minimum losses for the overall system.

VI. CONCLUSION

Voltage stability problems, once associated primarily with weak systems and long lines, are currently a source of concern in highly developed systems as a result of heavy loading. In this paper, the application of network reconfiguration technique for power network has been proposed for enhancement of voltage stability. The results obtained from the present study clearly indicate that the change of system configuration has significant impact on the voltage stability. Therefore, restructuring of system topology can improve voltage stability without involving any additional hardware and equipment cost. The present work conclusively demonstrates that for any given loading and generation condition, it is always possible to find out an optimum configuration for a power network, which can result best voltage stability for the whole system. It can also be concluded that improvement of voltage stability is associated with the reduction in overall power losses in the system and in most cases, the best voltage stability is achieved when power losses in the system are at the minimum value.

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