LOSS REDUCTION AND SECURITY ENHANCEMENT IN LOADED POWER SYSTEMS

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Abstract: This paper deals with the optimal expansion planning required for satisfying the continuous growth of load demand by preserving a liable level of network performances. Line loss participation factors and line stability levels are introduced to determine the lossiest/weakest lines. Furthermore, an algorithm for identifying the weakest and most vulnerable load buses is proposed. An original solution points out when, where and how if installing new lines and/or VAR sources, as a corrective measure, we minimize losses and enhance voltage stability. The IEEE 30 bus system is used to illustrate the capability and feasibility of the methodology.

Keywords: Voltage stability, Loss Participation Vector, Optimal Size, Optimal Location

1. INTRODUCTION

Due to the growth of loads and lack of transmission capability, power systems have been operated under stressed conditions and the ability to maintain system performance around its reliable level has become a growing concern. The choice of an optimal transmission network expansion plan is a difficult task. Many efforts have been done in this area. Over the last two decades, VAR planning has attracted a great deal of attention from both industry and academics. The goal has been focused on proving VARs at some specified buses to minimize losses and maintain voltage profiles within specified levels.

Over the last decade, due to many blackouts all over the world, system security became attractive and many methods have been proposed to allocate additional VAR sources to guarantee that there is no voltage collapse as the load varies.

Farrag, 1997 proposes a method to identify the weakest load buses in a network and considered them as the best locations for allocating additional VAR sources and then search for the optimal sizes of these VARs. The major objective was system security margin robustness, see Abdul-Rahman et al., 1995. Chen and Liu, 1994, Farrag, 1995, and Canizares, 1995, have presented new formulations for VAR planning, treating it as a constrained, multi-objective, non-differentiable optimization problem. The objectives were some or all of the following: real power loss reduction, minimization of the cost of the investment VAR sources, system security margin robustness and reduction of the voltage deviation of the system.

Chebbo et al., 1992, Granville and Lima, 1995, have addressed some of the basic issues of the voltage stability problem and VAR planning. Ekwue and Cory, 1984, have proposed an approach based on a single-stage optimization method in order to transmit power from new generating station to the loaded system.

Hong and Gau, 1994, have presented a method for identifying the weakest bus/area that is most likely to cause voltage collapse. Mohamed and Jasmon, 1995, have presented two methods of identifying the bus clusters in order to identify the weak and strong areas in a network.

Zalapa and Cory, 1995, have developed a procedure for allocating reactive reserves in order to avoid any voltage collapse. Zambroni and Quintana, 1994, have presented an approach to identifying the margins in power systems in relation to voltage collapse.

In this paper, an algorithm for deciding when, where and how to install new lines and/or new reactive power sources to satisfy the continuous growth of load demand at a reliable level of system level of system performance is presented.

2. SOLUTION METHODOLOGY

The first step in rehabilitating a network to maintain a reliable level of system performance is to identify the weak elements and schedule a priority list ordering vector based on their weakness to take place within a plan horizon. In the following sections a global methodology for determining the weakest and the lossiest line, as well as for finding the weakest and most vulnerable nodes in the network is proposed.

The solution optimizes the size and location of new lines and new VARs. The objectives are the minimum real power losses, robust voltage stability margin and the maximum overall investment.

2.1 Line Loss Participation Factors

As in Manescu, 2002, for transmission line k terminated by nodes i and j (Fig. 1), the real power losses through the line may be calculated as:

$$P_{Lk} = \mathrm{Re}\left(\underline{S}_{ij} - \underline{S}_{ji}\right), k \in NL \qquad (1)$$

and the total transmission losses are:

$$P_{Lt} = \sum_{k=1}^{NL} P_{Lk} \qquad (2)$$

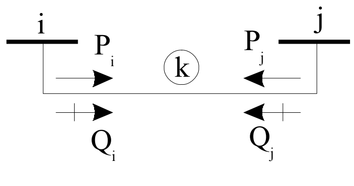

Fig. 1 Two bus system

To determine the loaded and most lossy line in a network, a participation loss factor for line k is defined as:

$$LPF_k = \frac{P_{Lk}}{P_{Lt}}, k \in NL \qquad (3)$$

The line loss participation factors for all lines are calculated and ranked in a descending order to obtain the loss participation vector, LPV. The first element in LPV points the lossiest line in the network to be reinforced. The second element is the second line to be reinforced and so on.

2.2 Line Stability Factors

As shown in Fig. 1, if the power flows from node i to node j and note i is taken as a reference node:

$$\underline{S}_i = \underline{S}_j + \underline{Z}_k \left(\frac{\underline{S}_i^*}{\underline{V}_i^*} \right)^2$$

$$P_i + jQ_i = P_j + jQ_j + \left(R_k + jX_k\right) \frac{\left(P^2 + Q^2\right)}{V_i^2}$$

from witch real and imaginary parts are separated as:

$$\left(\frac{R_k}{V_i^2}\right) P_i^2 - P_i + \left(P_j + Q_i^2 \frac{R_k}{V_i^2} \right) = 0 \qquad (4)$$

$$\left(\frac{X_k}{V_i^2}\right) Q_i^2 - Q_i + \left(Q_j + P_i^2 \frac{X_k}{V_i^2} \right) = 0 \qquad (5)$$

For real roots, the discriminate of equations (4) and (5) should be positive and hence the line stability factors LSP_k and LSQ_k are:

$$LSP_k = 4 \left(\frac{R_k}{V_i^2}\right) \left(P_j + Q_i^2 \frac{R_k}{V_i^2} \right) = 0 \qquad (6)$$

$$LSQ_k = 4 \left(\frac{X_k}{V_i^2}\right) \left(Q_j + P_i^2 \frac{X_k}{V_i^2} \right) = 0 \qquad (7)$$

The voltage stability level of a line k is defined as:

$$LSL_k = Max\left(LSP_k, LSQ_k\right) \qquad (8)$$

The closer the factor LSL_k is to 1.0, the weaker the line k is from the viewpoint of voltage stability, as said Pal, 1992. The line stability levels for all lines are calculated and ranked in a descending order to obtain the line stability vector, LSV.

2.3 Optimal Locations of New VARs

For a system of n_l load buses, Thevenin equivalent matrix $\left[\underline{Z}_{th}\right]$, is partitioned so that the elements identified with fixed load buses are separated from the other elements by horizontal and vertical lines, [1]. The partitioned matrix is:

$$\left[\underline{Z}_{th}\right] = \begin{bmatrix} \left[\underline{Z}_{th1}\right] & \left[\underline{Z}_{th2}\right] \\ \left[\underline{Z}_{th3}\right] & \left[\underline{Z}_{th4}\right] \end{bmatrix} \qquad (9)$$

<u>*Critical Voltages for Buses of Varying Loads*</u>: The multi-port Thevenin equivalent network in schematic form with a representative bus i, where the bus i belongs to n_v varying load buses, is shown in Fig. 2.

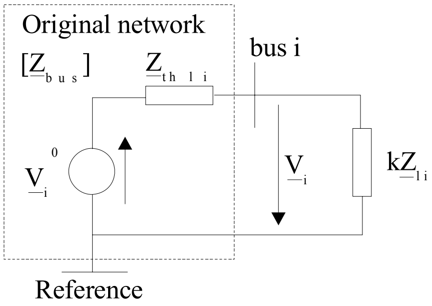

Fig. 2 Thevenin equivalent network

Additional load impedance of $k[\underline{Z}_l]_{(n_l \times n_l)}$ is connected to the system. If $[\underline{V}]^0 = [\underline{V}_1^0, \underline{V}_2^0, ..., \underline{V}_{n_l}^0]^T$ is the open circuit voltage vector, the load current vector, as a function of k, is:

$$[\underline{I}] = [\underline{I}_1, ..., \underline{I}_{n_l}]([\underline{Z}_{th1}] + k[\underline{Z}_l])^{-1} \cdot [\underline{V}^0] \quad (10)$$

and the terminal load voltage vector is:

$$[\underline{V}] = k[\underline{Z}_l] \cdot ([\underline{Z}_{th1}] + k[\underline{Z}_l])^{-1} \cdot [\underline{V}^0] \quad (11)$$

and hence, the incremental real power transfer to the load is:

$$P = Real([\underline{V}]^T \cdot [\underline{I}]^*) \quad (12)$$

Varying k within a suitable range in small steps and finding the corresponding incremental active power in each step, the value of k, which yields maximum power transfer, can be specified. Substituting about the specified value of k in equation (11) gives the critical voltages of varying load buses, $\underline{V}_{crl_v}$.

Critical Voltages for Buses of Fixed Loads

The voltage drop across Thevenin equivalent elements due to a change in loads at n_v busses is:

$$\begin{bmatrix} [\Delta \underline{V}_v] \\ [\Delta \underline{V}_w] \end{bmatrix} = \begin{bmatrix} [\underline{Z}_{th1}] & [\underline{Z}_{th2}] \\ [\underline{Z}_{th3}] & [\underline{Z}_{th4}] \end{bmatrix} \cdot \begin{bmatrix} [\underline{I}_v] \\ [\underline{I}_w] \end{bmatrix} \quad (13)$$

Because is no change in loads at n_w load busses, $[\underline{I}_w] = 0$. Hence, $[\Delta \underline{V}_w]$ as a function of $[\Delta \underline{V}_v]$, from equation (13), may be driven at the instant of the critical voltage occurrence as:

$$[\Delta \underline{V}_v] = [\underline{Z}_{th1}] \cdot [\underline{I}_v] \quad (14)$$

$$[\Delta \underline{V}_w] = [\underline{Z}_{th3}] \cdot [\underline{Z}_{th1}]^{-1} [\Delta \underline{V}_v] \quad (15)$$

Thus, the critical voltages at fixed load buses $[\underline{V}_{crl_w}]$ are:

$$[\underline{V}_{crl_w}] = [\underline{V}_w^0] - [\Delta \underline{V}_w] \quad (16)$$

and hence, the vector of critical voltages for varying and fixed buses is:

$$[\underline{V}_{crl}] = [[\underline{V}_{crl_v}] \ \ [\underline{V}_{crl_w}]]^T \quad (17)$$

A voltage collapse index, (VCI_i), for identifying the weakest bus in the network is defined as:

$$VCI_i = \frac{V_i^0 - V_{crl_i}}{V_{crl_i}} \quad (18)$$

For a secure system, all V_{crl_i} at all load buses must lie within a narrow range of small values.

2.4 Optimal Sizes of New VARs

To catch the optimal sizes of additional compensation at the selected locations, the following procedure is followed:

1) A small value of VAR is installed at the node of maximum VCI_i and the updated vector of VCI is calculated.
2) An increment ΔVAR is added gradually at the compensated node and step 1) is repeated until there is no further reduction of VCI or the total installed value of VAR exceeds its limits.
3) The node of second maximum VCI_i takes its places and is manipulated similarly as the foregoing node. Although there was no further reduction in VCI, when manipulating this foregoing node. It is noted that if the installed value of VARs at the present node exceeded the value of VARs at the foregoing node, without constraints limitations, additional VARs at the foregoing node may lead to a new reduction in VCI.
4) Continue with the third maximum node and so on.

The above procedure gives n sub-optimal solutions corresponding to one vulnerable node, two vulnerable nodes, until the n vulnerable nodes. To determine which of the given solutions is the optimal one, an investment cost function in introduced as:

$$f = Max(k_e \cdot l_{osf} \cdot \Delta P_{loss} - k_{var} \cdot \sum \text{VARs}) \quad (19)$$

The above function leads to the optimal number of vulnerable nodes to be compensated to reduce the risk of voltage collapse and maximize savings due to power loss reduction. The overall methodology may be depicted as shown in the flowchart in Fig. 3.

The time horizon for adding new lines or installing VAR sources depends on the required system quality and level of reliability for the network performance. As shown above, it is easy to ask to use the proposed indices regularly with the growth of load demand to determine the vulnerable elements in the network and weakness degree. Thus, the priority of reinforcement for each element can be scheduled and/or updated regularly according to the present circumstances.

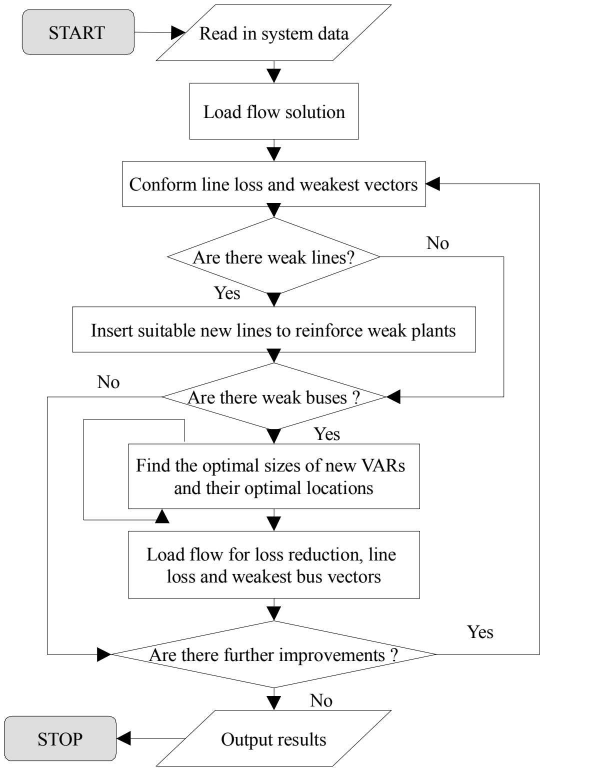

Fig. 3 : Flowchart of the solution methodology

3. NUMERICAL RESULTS

The verification of the proposed methodology is done through an analysis of the system performance within the IEEE 30-bus system (Fig. 4).

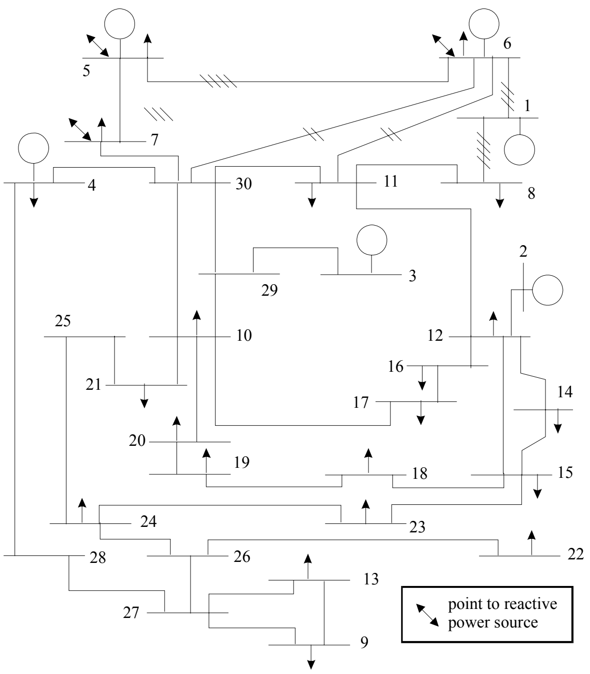

Fig. 4 : Modified IEEE 30 bus system

Table 1 gives the line data of the system. Thirty percent of the load demand has been increased to simulate the situation at a certain time horizon.

Table 1 Line data of the IEEE 30 bus system

Line no.	Bus code From	Bus code To	Series impedance	½ Shunt impedance
1	1	6	0.192+j0.0575	0.0264
2	1	8	0.0452+j0.1852	0.0204
3	6	11	0.057+j0.0575	0.0184
4	8	11	0.0132+j0.1852	0.0042
5	6	5	0.0472+j0.1737	0.0209
6	6	30	0.0581+j0.0379	0.0187
7	11	30	0.0119+j0.0414	0.0045
8	5	7	0.046+j0.116	0.0102
9	30	4	0.0267+j0.082	0.0085
10	30	4	0.012+j0.042	0.0045
11	30	29	0+j0.2112	0
12	30	10	0+j0.5354	0
13	29	3	0+j.0208	0
14	29	10	0+j0.11	0
15	11	12	0+j0.2593	0
16	12	2	0+j0.14	0
17	12	14	0.1231+j0.2559	0
18	12	15	0.0662+j0.1304	0
19	12	16	0.0945+j0.1987	0
20	14	15	0.221+j0.1997	0
21	16	17	0.0824+j0.1932	0
22	15	18	0.107+j0.2185	0
23	18	19	0.0639+j0.1292	0
24	19	20	0.34+j0.068	0
25	10	20	0.0936+j.0209	0
26	10	17	0.0324+j0.0845	0
27	10	21	0.0348+j0.0749	0
28	10	25	0.0727+j0.1499	0
29	21	25	0.0116+j0.0236	0
30	15	23	0.1+j0.202	0
31	25	24	0.115+j0.179	0
32	23	24	0.132+j0.27	0
33	24	26	0.1885+j0.3292	0
34	26	22	0.2544+j0.38	0
35	26	27	0.1093+j0.2087	0
36	28	27	0+j0.3794	0
37	27	9	0.2198+j0.4153	0
38	27	13	0.3202+j0.6027	0
39	9	13	0.2399+j0.4533	0
40	4	28	0.0638+j0.2	0
41	30	28	0.0169+j0.0599	0

Table 2 consists of five cases. Each one has four main columns to indicate, consequently, the lossiest lines, weakest lines from the point of voltage stability levels, weakest node, which can cause voltage collapse and real power losses.

Table 2 System performance through levels of modification

Case	Most lossy lines		Weakest stability lines		Vulnerable nodes		Real losses [MW]
	Line no.	LPF	Line no.	LSL	Node no.	VCI	
I	5*	0.46	2	0.379	5	4.66	15.25
	1*	0.218	6	0.186	6	4.31	
	2*	0.075	3	0.184	14	3.48	
	8	0.033	38	0.178	18	2.68	
	6	0.026	8	0.175	19	2.53	
	18	0.023	39	0.141	20	2.44	
II	5	0.226	6*	0.185	5	5.26	7.42
	1	0.192	3*	0.184	6	4.78	
	2	0.085	8*	0.181	14	1.80	
	8	0.066	38	0.177	7	1.64	
	6	0.046	2	0.174	18	1.43	
	18	0.048	39	0.14	20	1.37	
III	1	0.243	2	0.205	5*	4.76	6.87
	5	0.24	38	0.175	6*	4.26	
	2	0.064	39	0.139	7*	1.83	
	18	0.05	33	0.118	14	1.70	
	38	0.042	17	0.099	18	1.34	
	6	0.041	32	0.097	8	1.33	
IV	1*	0.345	2*	0.479	6	2.72	7.88
	5	0.202	38	0.171	5	2.18	
	2	0.063	1	0.144	7	2.10	
	18	0.042	39	0.135	14	1.77	
	38	0.036	33	0.115	8	1.36	
	6	0.037	17	0.097	18	1.31	
V	1	0.269	2	0.272	6	2.57	6.82
	5	0.235	38	0.172	7	2.18	
	18	0.049	39	0.136	5	2.01	
	2	0.045	33	0.116	14	1.79	
	4	0.043	1	0.11	8	1.36	
	38	0.042	17	0.098	18	1.33	
	6	0.034	32	0.096	19	1.26	
	27	0.030	20	0.09	4	1.22	

* Refers to object which needs reinforcement

In *case I*, an increase of 30% in the system load demand is assumed and the corresponding results are tabulated. Of course, the system will suffer from high losses and low voltage stability levels on lines and may contain vulnerable nodes.

In *case II*, taking line loss participation factors into consideration, the lossiest lines were lines 5, 1 and 2 respectively. Line number 5 is reinforced with another three similar lines; each has the same cross-sectional area as line 5 and connected in parallel with it between nodes 6 and 5. For lines 1 and 2, each is reinforced with one similar and parallel with it. It is noted that:

- real power losses are greatly reduced;
- although line voltage stability levels are enhanced, the probability of occurring voltage collapse is increased.

In *case III*, looking for the stability levels, lines 8, 3 and 8 arose to be the weakest lines. They are reinforced by connecting a parallel line to each with the same cross-sectional area as its conjugate. It is noted that:

- a further reduction in real power losses has occurred;
- the probability of occurring voltage collapse is nearly reduced to its original case (case I).

In *case IV*, an algorithm searching for the optimal sizes and numbers of new VARs to be inserted at the vulnerable nodes in order to reduce the risk of voltage collapse with maximum cost investment is applied. The optimal locations were at node numbers 5, 6 and 7, with optimal values of 0.2, 0.4 and 0.2 respectively. l_{osf} is taken equal to 0.55, k_e is adopted to be 0.02$/kWh and k_{var} is 14.38$/kVAR/yr. It is noted that;

- although real power losses are slightly increased, there was an appreciable enhancement in voltage collapse index;
- Lines 1 and 2 require further reinforcement and that which is done in case V.

In *case V*, the line 5 is reinforced with another line connected in parallel with the group between nodes 1 and 6 and has a cross-sectional area similar to each line of the parallel group. Line 2 is reinforced with two parallel lines connected with the parallel group between lines 1 and 8 and all lines are of similar cross-sectional area. This case offers the optimal plan horizon, in which the real power losses are reduced by about 55.28% and voltage collapse index is improved by about 44.9%. Consequently, voltage profile is improved and the system became most robust and secure. The modified system is shown in Fig. 4.

Also, the developed methodology is applied on larger test case and more complicated constraints to test its applicability, capability and robustness. The results were very promising. The more heavily loaded the network is, the greater the gained benefits are.

4. CONCLUSIONS

A new methodology is proposed for pointing out:

- the lossiest line;
- the stability level of the lines;
- the nodes exposed to voltage collapse.

The proposed methodology can easily decide when, where and how to install new lines and/or new reactive power sources in order to maximize loss reduction and reduce the risk of voltage collapse in the system.

This methodology has been tested on several power systems with different sizes, in order to evaluate its feasibility and capability.

The numerical results on the IEEE 30 bus system indicate that this methodology is a powerful and promising tool for planners.

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