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Voltage Stability and Loading Margin Improvement in Power System by Optimal Placement of SVC

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Abstract – **Proper installation of flexible ac transmission systems (FACTS) in existing transmission networks can improve transmission system loading margin (LM) to a certain degree and reduce network expansion cost. In the paper, under each contingency with high risk index (RI) value, the modal analysis (MA) technique is used to determine which buses need static var compensator (SVC) installation, and with maximum LM and minimum SVC installation cost composed into the multi-objective function the optimal LM enhancement problem is formulated as a multi-objective optimization problem (MOP) and solved by using the fitness sharing multi-objective particle swarm optimization (MOPSO) algorithm for a Pareto front set. In the Pareto front set for each considered contingency, the solution with the biggest performance index value is determined for SVC installation. Finally, an SVC installation scheme derived from the union of the SVC installations for all considered contingencies is recommended for LM enhancement. The proposed method is validated on the IEEE 30-bus reliability test system (RTS) and a practical power system.**

Keywords: **Continuation Power Flow, Loading Margin, Modal Analysis, Pareto Front, Risk Index, Static Voltage Stability**

I. Introduction

Under urgency to diminish the harms from environmental deterioration, one of the recently focused researches in the power industry is to make the existing transmission networks sufficiently utilize their capability in power transfer. Through detailed studies, voltage instability was found to be the main factor responsible for several blackout events in the recent years. A flexible alternating current transmission system (FACTS) is a system composed of static equipment used for the AC transmission of electrical energy. It is meant to enhance controllability and increase power transfer capability of the network. It is generally a power_electronics-based system. FACTS is defined by the IEEE as “a power electronic based system and other static equipment that provide control of one or more AC transmission system parameters to enhance controllability and increase power transfer capability.

The deregulation of the electricity market together with increasing constraints resulting from social opposition to the installation of new facilities puts new demands on the operators of transmission and distribution systems. These new trends enhance the need for flexibility, power quality and increased availability of transmission and distribution systems by using tools which can be implemented with limited investments, short delivery times and short planning and decision making horizons. FACTS (Flexible AC Transmission Systems) are a term denoting a whole family of concepts and devices for improved use and flexibility of power systems. Some of these devices have today reached certain maturity in their concept and application; some are as a matter of fact quite established as tools in power systems. This paper will treat benefits of FACTS devices applied in power systems such as increased power transmission capability, improved static and dynamic stability, an increase of a availability and a decrease of transmission losses. Examples will be given of FACTS devices which have reached a more or less commercial degree of applicability in power systems, salient design features of these as well as operational experience.

The traditional way to develop the transmission network in order to achieve better linkage between generation and demand was to reinforce of the grid, mainly by installing new lines and substations. However, in recent years substantial changes were implemented in the traditional structures of electric power systems throughout the world. The general reason for this is to improve efficiency, and the main tools are deregulation and privatization i.e. the introduction of market rules to the electrical sector. In consequence the transmission system must be adapted to the new conditions of open access and open trading. This adaptation requires the construction of new interconnections between regions and countries. The other important element is the necessity to adapt transmission systems to changing generation patterns. Manufacturers of electrical equipment must be prepared to meet these new requirements, where relocatability and flexibility will be the critical factors. The flexibility of the system also means shorter planning and decision-making, with the consequence that shorter delivery times are requested. Practical examples of how these new requirements can be satisfied by using new types of equipment are described below.

Transmission of electric energy at EHV (extra high voltage) over a long distance by means of alternating current (AC), requires some kind of reactive compensation. This is due to the inherent distributed series reactance and shunt susceptance of the long AC transmission line. If suitable means for reactive compensation are not installed, operation of the EHV power system for different steady state and dynamic conditions becomes difficult and even impossible. Basically, reactive compensation may be applied to the power system in two ways:

Series compensation and shunt compensation. Usually, shunt compensation is employed for voltage control and series compensation to control the longitudinal behavior of the network. The series capacitor is a special case of controlling the power transmission system through control of a longitudinal element, i.e. an element that is placed lengthwise in the transmission line. This is in contrast to shunt element controls, such as the control of generation, of loads or using static var compensators. However, each type of compensation affects, to some extent, both the voltage control and the stability limit. In an actual long distance EHV AC transmission system, means for series and shunt compensation are often combined in order to achieve the optimal result.

In this paper, under each contingency with high risk index (RI) value, the modal analysis (MA) technique is used to determine which buses need static var compensator (SVC) installation, and with maximum LM and minimum SVC installation cost the optimal LM enhancement problem is formulated as a multi-objective optimization problem (MOP) and solved by using the fitness sharing multi-objective particle swarm optimization (MOPSO) algorithm for a Pareto front set.

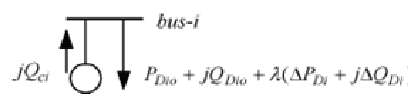


Fig.1 PQ bus with an SVC installation

A static synchronous compensator (STATCOM), also known as a “static synchronous condenser” (“STATCON”), is a regulating device used on alternating current electricity transmission networks. It is based on a power electronics voltage-source converter and can act as either a source or sink of reactive AC power to an electricity network. If connected to a source of power it can also provide active AC power. It is a member of the FACTS family of devices.

Increased use of transmission facilities due to higher industrial output and deregulation of the power supply industry have provided the momentum for exploring new ways of maximizing power transfers in existing transmission facilities while, at the same time, maintaining acceptable levels of network reliability and stability. In this environment, high performance control of the power network is mandatory. The possibility of controlling power flow in an electric power system without generation rescheduling or topology changes can improve the power system performance. By use of controllable components, the line flows can be changed in such a way that thermal limits are not exceeded, losses minimized, stability margins increased, contractual requirement fulfilled, etc. without violating the economic generation dispatch.

Recent break-throughs in power electronics technology have enabled the development of a variety of sophisticated controllers used to solve long-standing technical and economical problems found in electrical power systems at both the transmission and distribution levels. These emerging controllers are grouped under the headings FACTS and custom power technology respectively. FACTS is one aspect of the power electronics revolution that is taking place in all areas of electric energy. A variety of powerful semiconductor devices not only offer the advantage of high speed and reliability of switching but, more importantly, the opportunity offered by a variety of innovative circuit concepts based on these power devices enhance the value of electric energy.

The use FACTS devices in a power system can potentially overcome limitations of the present mechanically controlled transmission systems. By facilitating the bulk power transfers, these interconnected networks minimize the need to enlarge power plants and enable neighboring utilities and regions to exchange power. The stature of FACTS devices within bulk power system will continually increase as the industry moves toward a more competitive posture in which power as bought and sold as a commodity. As power wheeling becomes increasingly prevalent, power electronic devices will be utilized more frequently to insure system reliability and stability and to increase maximum power transmission along various transmission corridors.

The basic operating requirements of an ac power system are that the synchronous generators must remain in synchronism and the voltages must be kept close to their rated values . The capability of a power system to meet these requirements in the face of possible disturbances (line faults, generator and line outages, load switching's, etc.) is characterized by its transient, dynamic, and voltage stability. The stability requirements usually determine the maximum transmittable power at a stipulated system security level In this paper, a two-machine power system has been considered for describing the impact of STATCOM in enhancing the transient stability of the power system in the event of a three-phase fault near a bus. This paper investigates the changes in terminal voltages of the two machines, machines speeds and rotor angle difference between the two machines with and without STATCOM, when the fault occurs. Simulation results for the case study conducted on the two machine system are also presented.

From previous reviews, a FACTS installation problem can adopt linearization approaches, or methods with more flexibility including heuristic models and evolutional algorithms. In the paper, both concerns are dealt with at one time. First the risk index (RI) is used to assess the risk level caused by each contingency, and the contingencies with values bigger than the specified are considered for SVC installation. Then, under each considered contingency, MA technique is used to determine which buses need SVC installation, and the LM enhancement problem to determine the capacity of each SVC installation and generation pattern [6] is formulated as an MOP with maximum LM and minimum SVC installation cost involved in the multi-objective function. The fitness sharing MOPSO algorithm is used to solve for a Pareto front set from the MOP for each considered contingency. Also, the performance index, defined as the ratio of the LM to the installation cost, is used to determine a solution from the Pareto front set with LM bigger than or equal to the required LM. Finally, the locations and capacities for SVC installation derived from the union of the solutions for all considered contingencies are taken as the optimal SVC installation for LM enhancement, resulting in that the static voltage stability under each contingency can be maintained for allowable load increases.

Typically, an SVC comprises one or more banks of fixed or switched shunt capacitors or reactors, of which at least one bank is switched by thyristors. Elements which may be used to make an SVC typically include:

- Thyristor controlled reactor (TCR), where the reactor may be air- or iron-cored
- Thyristor switched capacitor (TSC)
- Harmonic filter(s)
- Mechanically switched capacitors or reactors (switched by a circuit breaker)

By means of phase angle modulation switched by the thyristors, the reactor may be variably switched into the circuit and so provide a continuously variable MVAR injection (or absorption) to the electrical network. In this configuration, coarse voltage control is provided by the capacitors; the thyristor-controlled reactor is to provide smooth control. Smoother control and more flexibility can be provided with thyristor-controlled capacitor switching.

Thyristor Controlled Reactor (TCR), shown with Delta connection Thyristor Switched Capacitor (TSC), shown with Delta connection The thyristors are electronically controlled. Thyristors, like all semiconductors, generate heat and deionized water is commonly used to cool them. Chopping reactive load into the circuit in this manner injects undesirable odd-order harmonics and so banks of high-power filters are usually provided to smooth the waveform. Since the filters themselves are capacitive, they also export MVARs to the power system. More complex arrangements are practical where precise voltage regulation is required. Voltage regulation is provided by means of a closed loop controller. Remote supervisory control and manual adjustment of the voltage set-point are also common.

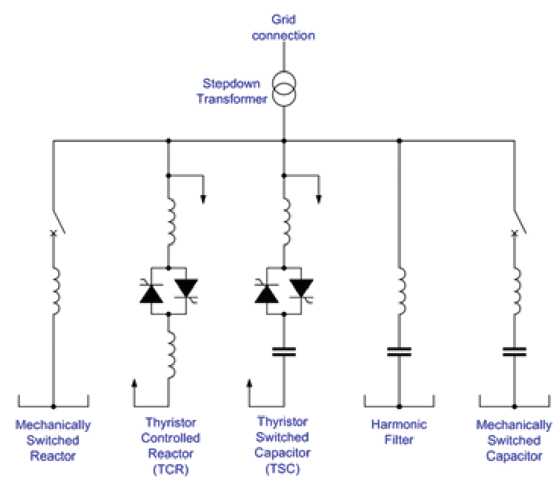


Fig. 2 Single line diagram of a typical transmission SVC containing a TCR, TSC, harmonic filter, mechanically switched reactor

The main advantage of SVCs over simple mechanically-switched compensation schemes is their near-instantaneous response to changes in the system voltage. For this reason they are often operated at close to their zero-point in order to maximize the reactive power correction they can rapidly provide when required. They are, in general, cheaper, higher-capacity, faster and more reliable than dynamic compensation schemes such as synchronous condensers. However, static VAR compensators are more expensive than mechanically switched capacitors, so many system operators use a combination of the two technologies (sometimes in the same installation), using the static VAR compensator to provide support for fast changes and the mechanically switched capacitors to provide steady-state VARs.

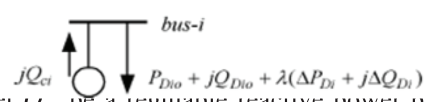
II. Problem Formulation

A. Multi-Objective Optimization Problems

When trying to solve an MOP, not only trying to look for one single solution but a set of trade-off solutions is the target of the solution algorithm and the one that will be chosen will depend on the needs of the decision maker. An MOP can be defined as

$$\begin{aligned} Min \quad & f(u) = [f_1(u), f_2(u), \ldots, f_k(u)]^{\mathrm{T}} \\ \text{s.t.} \quad & h(u) = 0 \\ & g(u) \leq 0 \end{aligned}$$

Where multi-objective function f includes $K(K \geq 2)$ objective functions, constraints $h(u)$ and $g(u)$ are equality and inequality functions, and is control variables. In order to optimize the vector function, the concepts tied to an MOP called "domination" and "non domination" are defined.



Let Q_{ci} be a regulable reactive power provided by the SVC at bus and its range is set to: $-Q_c \leq Q_{ci} \leq Q_c$ the equivalent injection for a PQ bus with an SVC installation. Employing CPF technique to formulate the LM enhancement problem and letting, λ=0for base load, the real and reactive power balance equations on bus i are expressed as,

$$\sum_{j=1}^{n} P_{ij} + P_{io} - \lambda(\Delta P_{Gi} - \Delta P_{Di}) = 0 \qquad (2)$$

$$\sum_{j=1}^{n} Q_{ij} + Q_{io} + \lambda(\Delta Q_{Di}) + Q_{ci} = 0. \qquad (3)$$

where system variables vector $x=[\theta \;\; V]^T$ including bus voltage magnitudes and phase angles, and control variables vector $u=[\Delta P_G \;\; Q_C]^T$ including the generation increments (or generation pattern) and reactive power injections Q_C of all SVC installations.

Also, the inequality constraints that should be satisfied with include the limits of real and reactive power generations, and the capacities of existing control devices (AVR, SC, OLTC) and SVC installations, expressed in an in equality functional vector as follows,

$$g(x, u, \lambda) \leq 0. \quad (7)$$

Based on specific control variables values, the maximum loading factor can be calculated using CPF process and the LM is derived as. The objective functions include maximum system LM (represented as), denoted as, and minimum SVC installation cost, denoted as. The two objective functions are integrated into a multi-objective function, expressed as a functional vector in the following,

$$f = [f_1\ f_2]^{\mathrm{T}}. \quad (8)$$

If five years is the lifetime for an SVC installation, the operating cost (US$/h) for all SVC installations is,

$$f_2 = \frac{\sum_{\forall i} (0.0003Q_{ci}^2 - 0.3051Q_{ci} + 127.38)10^5 \cdot Q_{ci}}{(5 \cdot 8760)}. \quad (9)$$

From (2) to (9), the LM enhancement problem with SVC installation is formulated as an MOP as follows,

$$\begin{aligned} &Min \quad f \\ &s.t. \quad h(x, u, \lambda) = 0 \\ &\qquad g(x, u, \lambda) \leq 0 \\ &\qquad\qquad 0 \leq \lambda. \end{aligned} \quad (10)$$

The MOP for each considered contingency is solved by using the fitness sharing MOPSO algorithm, and from the obtained Pareto front set, a solution with and maximum performance index value is determined for SVC installation, where represents the required LM.

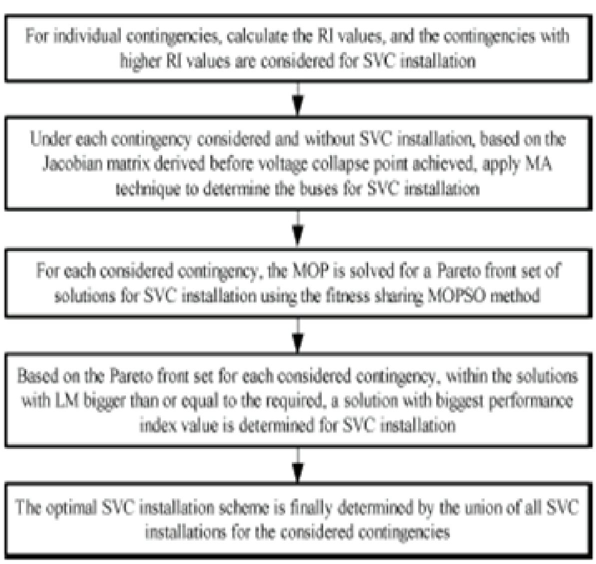


Fig. 3 Proposed LM enhancement strategy

Based on specific control variables values, the maximum loading factor can be calculated using CPF process and the LM is derived as. The objective functions include maximum system LM (represented as), denoted as, and minimum SVC installation cost,

B. Problem Formulation for Loading Margin Enhancement

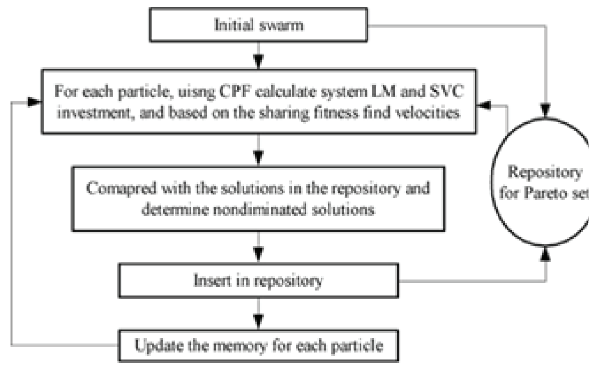


Fig.4 Block Diagram Of Proposed System

C. Outage Risk Index

In order to maintain system operating at static voltage stability under each outage, transmission systems need sufficient LM to avoid voltage instability while accommodating more power transfer. Since contingency events inevitably result in LM decrease, those contingencies with bigger failure probability and resulting in more LM decrease will have bigger values, namely requiring reactive power compensation. Under normal state and without SVC installation, the system LM represented as a loading factor is assumed to be. When contingency happens, the LM becomes, resulting in a decreased LM expressed. The value under contingency is calculated from,

$$Risk(E_i) = P_r(E_i) \times \Delta\lambda_{E_i} \quad (11)$$

where if the failure probability of contingency . The failure rate of the contingency is expressed as which can be obtained from the power supply department. It is assumed that the contingency events are independent, and under a contingency, during the period of voltage instability resulted from demand increase, the component is assumed not to be repairable. The failure rate is converted to the failure probability by a Poisson distribution.

$$P_r(E_i) = 1 + \frac{e^{-\alpha_{E_i} T_r} - 1}{\alpha_{E_i} T_r} \qquad (12)$$

Finally, the optimal SVC installation is resulted from the union of the SVC installations for all considered contingencies. It is conceivable that, compared to the SVC installation for each contingency, the optimal SVC installation would have bigger SVC units number, each SVC installation with bigger or equal capacity. Reactive power is the most important factor to voltage stability. From the expectation of the impact level on voltage stability from load increase, the signals on which buses the reactive power compensation is necessary for maintaining enough system LM can be obtained.

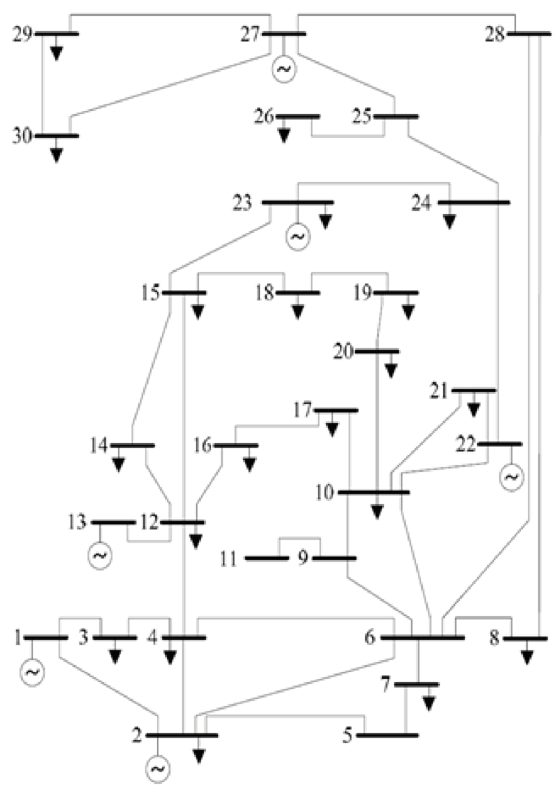


Fig. 5 30 Bus Reliability Test System

The existing method uses EGD, continuation power flow and other algorithms in the EGD algorithm it uses a 20 bus system and is not applied practically in the power system and other systems uses TCSR, TCSC, TCPST, and TCVR compensators which are expensive compared to SVC installation technique and not suitable for power system.

The proposed method linearly composed voltage security, system loss, capacities for STATCOM installation and LM into a single-objective function, which was solved by using a PSO algorithm.

While a single objective function was linearly composed of the installation costs for various types of FACTS devices (UPFC, TCSC, and SVC), system securities, and loss and voltage stability indices.

The problem was solved by PSO and GA. Besides, to possibly reveal the variety of solutions, the optimal SVC installation problem for LM enhancement is formulated as an MOP.

Line No.	From	To	X (p.u.)	Flow limit (MW)	Failure rate	Repair rate
1	1	2	0.06	130	0.9783	0.0217
2	1	3	0.19	130	0.9841	0.0159
3	2	4	0.17	65	0.9532	0.0468
4	3	4	0.04	130	0.9172	0.0828
5	2	5	0.20	130	0.9786	0.0214
6	2	6	0.18	65	0.9497	0.0503
7	4	6	0.04	90	0.9828	0.0172
8	5	7	0.12	70	0.9760	0.0240
9	6	7	0.08	130	0.9211	0.0789
10	6	8	0.04	32	0.9494	0.0506
11	6	9	0.21	65	0.9494	0.0506
12	6	10	0.56	32	0.9211	0.0789
13	9	11	0.21	65	0.9535	0.0465
14	9	10	0.11	65	0.9509	0.0491
15	4	12	0.26	65	0.9660	0.0340
16	12	13	0.14	65	0.9838	0.0162
17	12	14	0.26	32	0.9754	0.0246
18	12	15	0.13	32	0.9598	0.0402
19	12	16	0.20	32	0.9510	0.0490
20	14	15	0.20	16	0.9494	0.0506
21	16	17	0.19	16	0.9494	0.0506
22	15	18	0.22	16	0.9236	0.0764
23	18	19	0.13	16	0.9514	0.0486
24	19	20	0.07	32	0.9509	0.0491
25	10	20	0.21	32	0.9666	0.0334
26	10	17	0.08	32	0.9824	0.0176
27	10	21	0.07	32	0.9786	0.0214
28	10	22	0.15	32	0.9612	0.0388
29	21	22	0.02	32	0.9462	0.0538
30	15	23	0.20	16	0.9498	0.0502
31	22	24	0.18	16	0.9506	0.0494
32	23	24	0.27	16	0.9181	0.0819
33	24	25	0.33	16	0.9483	0.0517
34	25	26	0.38	16	0.9537	0.0463
35	25	27	0.21	16	0.9733	0.0267
36	28	27	0.40	65	0.9818	0.0182
37	27	29	0.42	16	0.9808	0.0192
38	27	30	0.60	16	0.9564	0.0436
39	29	30	0.45	16	0.9537	0.0463
40	8	28	0.20	32	0.9537	0.0463
41	6	28	0.06	32	0.9536	0.0464

Fig. 6 Line Parameters of the IEEE 30-Bus System

Unit	Bus	Cost coefficients			Pmax (MW)	Pmin (MW)	Min up time (h)	Min down time (h)	Ramp up (MW)	Ramp Down (MW)	Startup Ramp (MW)	Shutdown ramp (MW)
		A ($/MWh^2)	B ($/MWh)	C ($)								
G1	1	0.0200	15.00	0	80	15	2	2	25	25	70	60
G2	2	0.0175	14.75	0	80	15	2	2	25	25	70	60
G3	13	0.0250	16.00	0	50	10	3	3	15	15	70	60
G4	22	0.0625	14.00	0	50	10	4	4	15	15	70	60
G5	23	0.0250	16.00	0	30	5	3	3	10	10	70	60
G6	27	0.0083	15.25	0	55	10	4	4	15	15	70	60

Fig. 7 Reactive power limit of IEEE 30-Bus System

III. Test Results and Discussions

A. IEEE 30-Bus RTS

The IEEE 24-bus RTS with bus 13 as the swing bus, 10 PV bus and bus 14 connected with an AVR, and 34 transmission lines, shown in Fig. 5, is used for testing. The data of the transmission lines are shown in Table I, where line failure rates are shown in the last column, for example, that the rate of line 1 outage occurrences per year is 0.24 (Occ./yr). The base load and power supplies with 100 MVA as base are shown in Table.

The result explained below shows the various real and reactive power of various buses of the 30 bus test system.

Table I Power and Losses For The Unloaded Case

Bus No		Power at buses		Line Losses	
From	To	MW	MVAR	MW	MVAR
1	2	91.399	19.639	1.504	-1.284
	7	49.189	-7.003	1.001	-0.357
2	1	- 89.895	18.355	1.504	-1.284
	8	30.243	-7.641	0.495	-2.479
	3	57.656	6.915	1.477	1.813
	9	37.857	-5.758	0.772	-1.684
3	2	- 56.179	-5.103	1.477	1.813
	10	- 13.461	-1.895	0.083	-1.870
4	9	4.879	-21.637	0.054	-0.760
	28	0.121	-6.216	0.010	-4.483
5	11	17.930	11.002	0.000	-3.782
6	13	16.910	8.277	0.000	-1.899
7	1	- 48.188	6.646	1.001	-0.357
	8	45.788 -	7.846	0.262	-0.155
8	2	- 29.747	5.163	0.495	-2.479
	7	- 45.526	7.690	0.262	-0.155
	9	34.728	7.069	0.139	-0.478
	13	32.945 -	21.467	0.000	-0.858
9	2	- 37.085	4.074	0.772	-1.684
	8	- 34.588	-7.547	0.139	-0.478
	10	36.714	10.285	0.370	-0.640
	4	-4.825	20.877	0.054	-0.760
	11	22.757	-25.405	0.000	0.075
	12	17.137	-2.771	0.000	-3.188
	28	-0.110	0.353	0.002	-1.381
10	3	13.544	0.025	0.083	-1.870
	9	- 36.344	-10.925	0.370	-0.640
11	9	- 22.757	25.480	0.000	0.075
	5	- 17.930	-14.784	0.000	-3.782
	12	40.687	-10.697	- 0.000	-0.607
12	9	- 17.137	-0.417	- 0.000	-3.188
	11	- 40.687	10.089	- 0.000	-0.607
	20	10.022	-4.046	0.083	-4.431
	17	5.191	-0.059	0.009	-4.602
	21	23.934	-3.335	0.173	-1.934
	22	12.878	-4.232	0.110	-2.084
13	8	- 32.945	20.610	- 0.000	-0.858
	6	- 16.910	-10.176	0.000	-1.899
	14	8.686	-4.581	0.093	-2.121
	15	22.590	-9.611	0.332	-1.655
	16	7.379	-3.742	0.050	-2.209
14	13	-8.593	2.459	0.093	-2.121
	15	2.393	-4.059	0.017	-4.599
15	13	- 22.258	7.956	0.332	-1.655
	14	-2.377	-0.539	0.017	-4.599
	18	5.006	-2.173	0.024	-2.248
	23	11.428	-7.743	0.139	-4.326
16	13	-7.329	1.533	0.050	-2.209
	17	3.829	-3.333	0.011	-4.590
17	16	-3.818	-1.256	0.011	-4.590
	12	-5.182	-4.544	0.009	-4.602
18	15	-4.982	-0.075	0.024	-2.248
	19	1.782	-0.825	0.002	-2.284
19	18	-1.780	-1.459	0.002	-2.284
	20	-7.720	-1.941	0.018	-2.256
20	19	7.738	-0.315	0.018	-2.256
	12	-9.938	-0.385	0.083	-4.431
21	12	- 23.761	1.401	0.173	-1.934
	22	6.261	-12.601	0.017	-2.263
22	12	- 12.768	2.148	0.110	-2.084
	21	-6.243	10.339	0.017	-2.263
	24	19.012	-12.486	0.465	-3.869
23	15	- 11.289	3.418	0.139	-4.326
	24	8.089	-5.018	0.083	-4.423
24	22	- 18.547	8.617	0.465	-3.869
	23	-8.006	0.594	0.083	-4.423
	25	17.853	-15.912	0.830	-3.190
25	24	- 17.023	12.722	0.830	-3.190
	26	5.337	-3.435	0.073	-2.230
	27	11.686	-9.287	0.188	-1.998
26	25	-5.265	1.205	0.073	-2.230
	27	1.765	-3.505	0.000	-2.319
27	25	- 11.497	7.289	0.188	-1.998
	26	-1.765	1.186	0.000	-2.319
Total Loss				9.148	-94.924

TABLE II POWER AND LOSSES FOR THE CONGESTED CASE

Bus No		Real power		Reactive Power	
From	To	MW	MVAR	MW	MVAR
1	2	204.951	-11.901	7.329	16.272
	7	97.745	2.181	3.925	11.733
2	1	- 197.621	28.173	7.329	16.272
	8	52.987	-7.178	1.542	0.902
	3	101.170	- 1.782	4.609	15.101
	9	68.474	-8.084	2.620	4.109
3	2	-96.561	16.884	4.609	15.101
	10	-20.179	14.654	0.303	-1.242
4	9	-9.764	2.693	0.013	-0.861
	28	-0.236	- 2.532	0.000	-4.309
5	11	17.930	29.782	0.000	-2.138
6	13	16.910	34.615	0.000	-0.418
7	1	-93.820	9.552	3.925	11.733
	8	90.220	-11.352	1.059	2.182
8	2	-51.446	8.080	1.542	0.902
	7	-89.161	13.534	1.059	2.182
	9	68.803	-7.936	0.562	1.044
	13	60.403	-16.027	0.000	5.799
9	2	-65.854	12.193	2.620	4.109
	8	-68.242	8.980	0.562	1.044
	10	55.501	1.285	0.819	0.832
	4	9.777	-3.554	0.013	-0.861
	11	40.899	-19.683	0.000	2.277
	12	27.673	3.734	- 0.000	-0.149
	28	0.246 -	3.082	0.010	-1.305
10	3	20.482	-15.896	0.303	-1.242
	9	-54.682	-0.454	0.819	0.832
11	9	-40.899	21.960	0.000	2.277
	5	-17.930	-31.919	0.000	-2.138
	12	58.829	9.959	0.000	1.606
12	9	-27.673	-3.883	- 0.000	-0.149
	11	-58.829	-8.353	0.000	1.606
	20	14.459	-2.002	0.188	-3.695
	17	7.048	-0.090	0.017	-4.108
	21	36.514	8.745	0.477	-1.017
	22	19.781	2.583	0.282	-1.463
13	8	-60.403	21.827	0.000	5.799

TABLE III VARIOUS BUS VOLTAGES IN NORMAL AND CONGESTED CASES

Bus No.	Bus Voltages (pu) Normal case (Before Loading)	Congested case(After Loading)
1	1.0500	1.0500
2	1.0438	1.0238
3	1.0058	0.9958
4	1.0230	1.0030
5	1.0913	1.0913
6	1.0883	1.0883
7	1.0410	1.0145
8	1.0380	1.0075
9	1.0311	1.0029
10	1.0131	0.9874
11	1.0663	1.0306
12	1.0770	1.0207
13	1.0763	1.0425
14	1.0748	1.0271
15	1.0732	1.0176
16	1.0748	1.0271
17	1.0737	1.0169
18	1.0703	1.0070
19	1.0689	1.0029
20	1.0719	1.0077
21	1.0709	1.0014
22	1.0728	1.0017
23	1.0731	0.9947
24	1.0703	0.9676
25	1.0836	0.9240
26	1.0792	0.9001
27	1.0879	0.9068
28	1.0307	1.0039
29	1.0878	0.8867
30	1.0777	0.8669

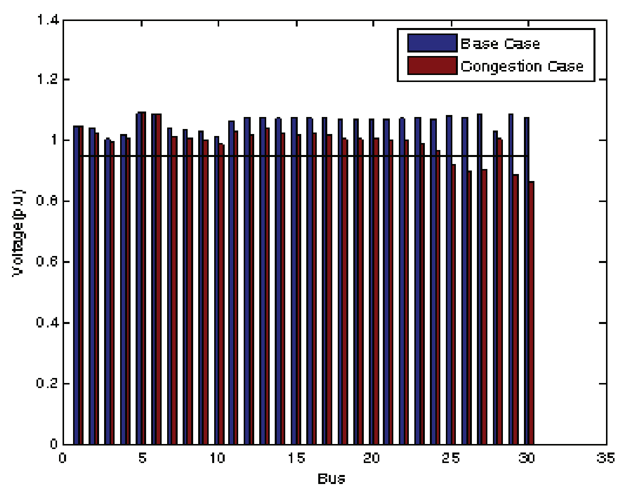


Fig. 8 Output voltages of each bus in P.U in base case and congestion cases.

Conclusion

The MOP proposed in the paper considering the most serious contingencies to seek a Pareto front set for each contingency is solved by using the fitness sharing MOPSO method. The proposed performance index is then used to determine an optimal SVC installation scheme for the required LM with the SVC installation locations and capacities derived from the union of the SVC installations for all considered contingencies. From the test results, the achievement of the proposed strategy for SVC installation, that is well consistent with specific economic and technical concerns, is validated.

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