

## Software Tool for Optimal Placement and Sizing of Shunt Var Compensators in Power Systems

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**Abstract:** This paper presents a MATLAB-based power system software tool, named as OPSVC for optimal placement and sizing of shunt Var compensators in both distribution and transmission systems. The OPSVC software incorporates the developed optimization algorithms and the backward/forward sweep power flow and radial harmonic power flow methods in an open source environment. The capabilities of the OPSVC are that it can conduct several analyses, such as load flow, optimal placement and sizing of shunt capacitors, Static Var Compensator (SVC) and Static Synchronous Compensator (STATCOM) using different optimization techniques and plotting voltage profile of the studied system before and after installing reactive power compensators.

### INTRODUCTION

Due to the limitations of the available power system analysis software tools and lack of heuristic optimization features in these tools, there is a strong motivation for developing a suitable software tool for optimal placement and sizing of shunt Var compensators in distribution and transmission systems incorporating heuristic optimization techniques. For this purpose, a new power system analysis tool called as Optimal Placement of Shunt Var Compensators (OPSVC) has been developed. To date, there is no such power system simulation package developed with features of heuristic optimization algorithms. The capabilities of the OPSVC are that it can conduct several analyses, such as backward/forward sweep power flow, radial harmonic power flow, optimal placement and sizing of capacitors, SVCs and STATCOMs using different optimization techniques and plotting voltage profile of the studied system before and after installing Var compensators

The MATLAB programming language is selected to implement the algorithms and routines in the OPSVC software. The MATLAB software which is short for MATrix LABoratory is a powerful and widely used tool for simulation. MATLAB includes tools that allow a program to interactively construct a graphical user interface (GUI) for the program. With this capability, a programmer can design sophisticated data analysis programs that can be operated by relatively inexperienced users (Altintas, 2011). In this work, MATLAB is chosen as the programming tool primarily because it offers several advantages such as graphics facilities,

interactive mode of work, simple programming and its wide availability on computing platforms. These factors make Matlab an excellent language for teaching and a powerful tool for solving research and practical problems. MATLAB implements GUI through the graphical user interface development environment (GUIDE) which allows a user to create figure windows containing graphical objects (Altintas, 2011). A GUI is a user interface program built with graphical objects such as buttons, text fields, sliders and menus. GUI ensures the communication process between a user and the MATLAB computational engine (Altintas, 2011). In this paper, the software development of the OPSVC software is discussed by describing the programming language used and the main structure of the software.

### Software Structure

All program modules in the OPSVC software have been developed in the MATLAB environment. The step-by-step procedures and calculations involved in the OPSVC are shown in Figure 1 and described as follows:

- i. Select the power system configuration which is either radial distribution system or transmission system.
- ii. Select the test system and the intended analysis. For analysis on a radial distribution system, the analyses include backward/forward sweep power flow, optimal placement and sizing of capacitors without harmonics consideration and optimal placement and sizing of capacitors

with harmonics consideration. For analysis on a transmission system, the analyses include power flow, optimal placement and sizing of SVC and optimal placement and sizing of STATCOM.

- iii. If the options of optimal placement and sizing of Var compensators are selected, the next steps are to:
  - a) Choose the intended optimization technique which may be Genetic Algorithm (GA), Particle Swarm Optimization (PSO), Harmony Search Algorithm (HS), Improved Harmony Search Algorithm (IHS) and Global Harmony Search Algorithm (GHS).
  - b) Execute the optimum placement and sizing program.
- iv. Display the obtained results and plot the voltage profiles

All the above-mentioned calculations are developed in MATLAB line codes and then integrated with the MATLAB GUI so as to produce a user-friendly interface.

**Main Modules of the OPSVC Software**

This section describes the main routines in the OPSVC software which consists of five main modules, namely test system selection, power flow analysis, optimization, voltage profile plotting and module for output data presentation.

**A. Test System Selection Module**

Figures 2, 3 and 4 show the interfaces of the OPSVC for test system selection. From the main interface of the OPSVC, as shown in Figure 2, a user can select the appropriate button depending on the intended system configuration for analyses. There are two system configurations for analyses, which are radial distribution systems and transmission systems.

For the radial distribution system interface as shown in Figure 3, a user has to specify the test system and the intended analysis which may be selected from the backward/forward sweep power flow, optimal placement and sizing of capacitors without harmonics consideration and optimal placement and sizing of capacitors with harmonics consideration. If a user selects the optimal placement and sizing analyses, an optimization technique must be selected from the GA, PSO, HS algorithm, IHS algorithm and GHS algorithm. If a user selects the optimal placement and sizing analysis with harmonic consideration, a harmonic source file is required to be selected.

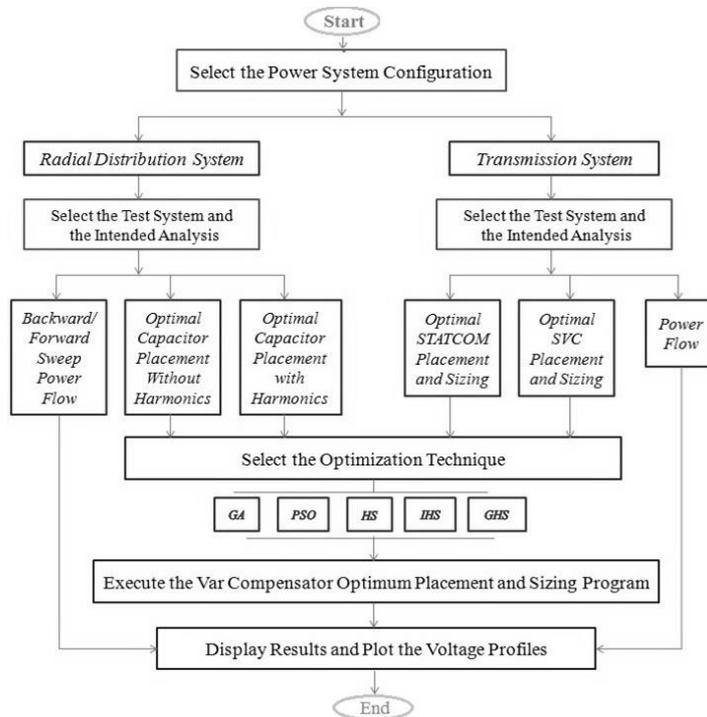


Fig.1: Procedure in the OPSVC

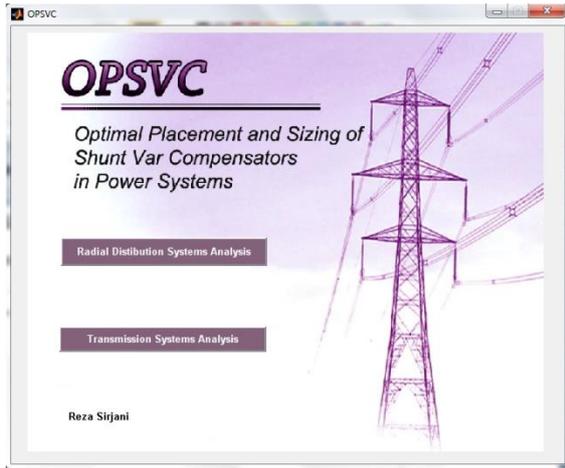


Fig. 2: The main page of the OPSVC software tool

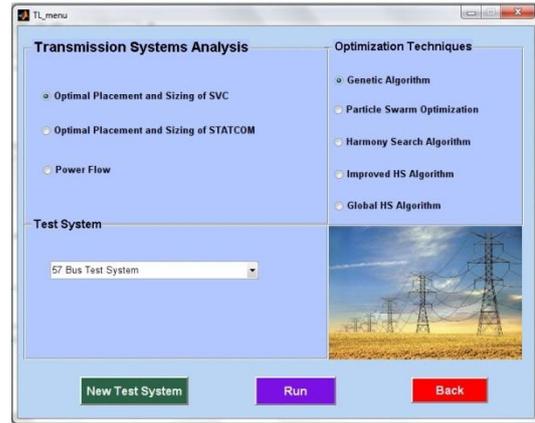


Fig. 4: Interface for transmission system analysis



Fig.3: Interface for radial distribution system analysis

In the OPSVC software tool, distribution system analysis can be performed on four test radial distribution systems, namely, the 10 bus system, 34 bus system, three-phase 10 bus system with harmonic sources and three-phase 34 bus system with harmonic sources. The line and load data of each test distribution system are already embedded in a file which is saved as "\*.rdt". For example the file "34\_Bus\_Test\_system.rdt" consists of 34 bus radial distribution system data. The data of harmonic sources are already embedded in a file which has been saved as "\*.rdh". For example the file "Harmonic\_Source\_34\_Bus.rdh" consists of the harmonic sources data for the 34 bus radial distribution system. A user can make a new test distribution system by creating a new "rdt" file. For this purpose, a user must click on the "New Test System" and form the line matrix and load matrix of the new system.

In the transmission system interface as shown in Figure 4, a user has to specify the test system and the intended analysis. The analyses include power flow, optimal placement and sizing of SVCs and optimal placement and sizing STATCOM. If a user selects the optimal placement and sizing analyses, an optimization technique must be selected from the GA, PSO, HS algorithm, IHS algorithm and GHS algorithm.

In OPSVC, two transmission systems, namely, the IEEE 57 bus system and the IEEE 118 bus system are considered as default test systems for transmission system analysis. The line, load and generator data of the transmission test system are embedded in a file which has been saved as "\*.tlt". For example the file "57\_Bus\_Test\_System.tlt" consists of 57 bus transmission system data. A user can make a new transmission test system by clicking on the "New Test System" and create a new "tlt" file.

### B. Power Flow Module

The widely used power flow solver based on the standard Newton Raphson technique is incorporated in the software tool. The background theory of the Newton Raphson power flow technique can be found in Tinney and Hart (1972); Stevenson and Jr (1982); Saadat (2002). By performing power flow analysis, the bus voltage magnitudes,  $|V_i|$  and angles,  $\delta_i$  can be determined.

For radial distribution networks, a simple power flow technique named as the backward/forward sweep power flow (Teng, 2000) is used because the method does not require the formation of the Jacobian matrix. Besides, a simple harmonic power flow that uses the backward and forward sweep method (Teng and Chang, 2007) has also been developed to calculate harmonic branch currents and harmonic nodal voltages. Figure 5 shows the output interface of the OPSVC software after performing power flow analysis on a test radial distribution system. The backward/forward sweep power flow and harmonic radial power flow which have been described in (Teng and Chang, 2007), are used together to calculate the voltage magnitude, voltage angle and THD at each bus. Figure 6 shows the power flow output for the 57 bus transmission system. The Newton-Raphson technique is used to calculate the voltage magnitude and voltage angle of each bus. The 57 bus transmission system data can be found in (Sirjani et al., 2011a)..

In both transmission and distribution power flow analyses, the results of line power flow have not been displayed on the GUI, but have been calculated and saved in a text file. A user can access all the power flow results by clicking on the “Report as File”. Figure 7 shows the line power flow results of the 57 bus transmission system which are reported in the form of a text file.

**C. Optimization Module**

Five heuristic optimization techniques, namely, GA, PSO, HS algorithm, IHS algorithm and GHS algorithm are used to solve the optimal shunt Var compensators problem. The detailed implementation procedures of these optimization techniques for finding the optimal solutions have been described in (Sirjani, 2012). Figure 8 shows the interface of optimal capacitor placement in a radial distribution system. This GUI form includes four sections: optimization parameters, studied cases, convergence characteristics and results of optimal capacitor placement. In the “optimization parameters” section, a user has to specify the required parameters of the selected optimization technique. In the “studied cases” section, a user can consider mutual coupling and load unbalance for solving the problem. For cases considering harmonics, the maximum value of THD has to be defined.

Line #	From Bus	To Bus	From Bus P (Mw)	Injection Q (MVar)	To Bus P (Mw)	Injection Q (MVar)	Loss P (Mw)	Loss Q (MVar)
1	1	2	102.24	74.95	-100.93	-84.07	1.317	4.44
2	2	3	97.93	-4.68	-95.13	4.53	2.801	7.99
3	3	4	60.21	-8.01	-59.79	5.72	0.423	1.38
4	4	5	13.78	-4.46	-13.65	2.26	0.130	0.27
5	4	6	14.14	-5.13	-14.05	2.11	0.095	0.33
6	6	7	-17.83	0.50	17.89	-2.81	0.067	0.34
7	6	8	-42.48	-6.57	43.13	5.22	0.644	3.28
8	8	9	178.40	18.79	-175.23	-9.02	3.169	16.17
9	9	10	17.26	-9.00	-17.13	5.36	0.133	0.60
10	9	11	12.94	2.76	-12.89	-4.67	0.049	0.16
11	9	12	2.34	-15.85	-2.44	8.64	0.104	0.47
12	9	13	2.33	-1.49	-2.32	-2.39	0.003	0.01
13	13	14	-10.28	23.15	10.37	-23.89	0.092	0.30
14	13	15	-48.94	4.88	49.62	-4.89	0.683	2.21
15	15	16	149.11	34.60	-145.19	-24.71	3.922	20.05
16	1	16	79.38	-0.87	-76.73	-1.12	2.647	12.01
17	1	17	93.47	3.93	-81.55	-1.79	1.929	8.75
18	3	15	33.91	-16.88	-33.69	12.33	0.226	0.74
19	4	18	13.98	2.54	-13.98	-1.45	-0.000	1.10
20	4	18	17.89	1.33	-17.89	0.05	-0.000	1.38

Fig.7 : The line power flow results for 57 bus transmission system

While the program is running, the convergence curve is plotted as shown in Figure 8. When the optimization procedure is completed, the optimal capacitor locations and sizes are displayed on the interface. The power loss, harmonic power loss, THD, investment cost and total cost after installing capacitors are also displayed on the interface. Figure 9 shows the interface for solving the optimal Var compensator placement problem. This GUI has four sections, namely, optimization parameters, Var compensator input data, convergence characteristics and results of optimal SVC/STATCOM placement. In the section “Var compensators input data”, a user has to specify the maximum range of Var compensators in MVar and also the number of Var compensator.

While the program is running, the convergence characteristic is plotted and when the optimization procedure is completed, the obtained optimal SVC or STATCOM location and size are displayed on the GUI. The power loss, voltage deviation, the smallest eigenvalue and investment cost after installing the Var compensators are also displayed on the interface.

**D. Voltage Profile Plotting Module**

In each analysis, after running the program, voltage profile of the studied system is plotted. Since voltage deviation minimization is one of the objective function in the optimal placement and sizing of shunt Var compensators in transmission systems, the OPSVC software can also plot the total voltage deviation curves before and after installation of Var compensators.

**E. Module for Output Data Presentation**

To obtain the output results in terms of a report, a text file is created by the OPSVC software for each analysis. By clicking on the “Report as File” button, the OPSVC software creates an output text file. Figure 10 shows a sample of an output text file which can be used as a report.

Bus No.	Voltage (mag)	Voltage (ang)	THD (%)
15	0.988	0.116	3.086
16	0.988	0.116	3.086
17	0.966	0.483	3.675
18	0.962	0.546	3.819
19	0.958	0.628	3.968
20	0.955	0.695	4.1
21	0.952	0.754	4.227
22	0.949	0.833	4.366
23	0.946	0.899	4.502
24	0.944	0.96	4.66
25	0.942	0.99	4.763
26	0.942	1.002	4.763
27	0.942	1.005	4.763
28	0.966	1.504	3.683
29	0.966	0.508	3.683
30	0.966	0.511	3.683
31	0.96	0.643	4.133
32	0.96	0.651	4.233
33	0.96	0.655	4.306
34	0.96	0.656	4.306

Fig.5 :The power flow output for a test radial distribution system

Bus No.	Voltage (mag)	Voltage (ang)
38	1.008	-0.222
39	0.977	-0.235
40	0.966	-0.238
41	0.994	-0.246
42	0.964	-0.271
43	1.009	-0.198
44	1.013	-0.207
45	1.034	-0.162
46	1.058	-0.194
47	1.03	-0.219
48	1.024	-0.22
49	1.033	-0.226
50	1.021	-0.235
51	1.051	-0.219
52	0.968	-0.196
53	0.955	-0.206
54	0.987	-0.201
55	1.028	-0.189
56	0.965	-0.26
57	0.961	-0.266

Fig.6 : The power flow output for the 57 bus transmission system



Fig.8: The interface for solving optimal capacitor placement problem

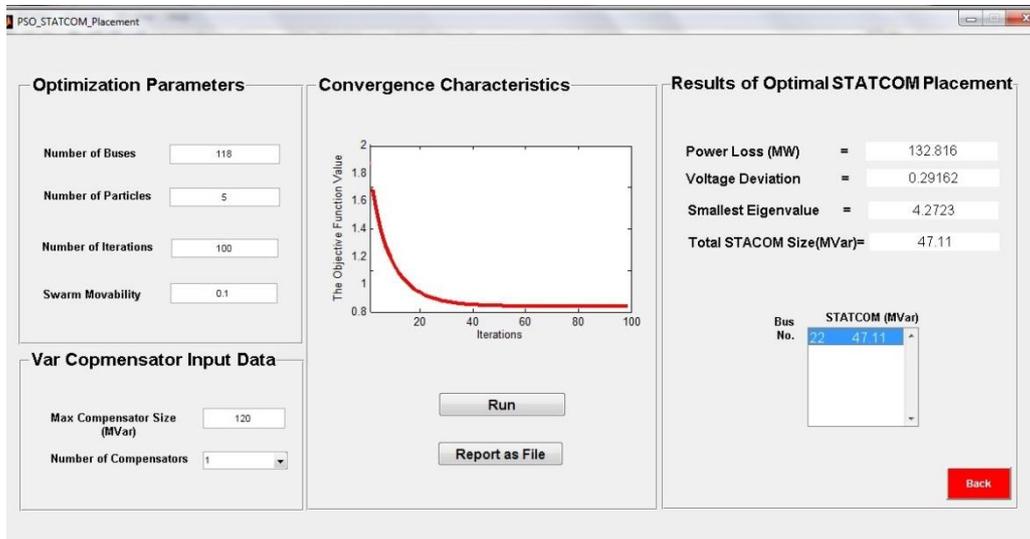


Fig.9: The interface for solving optimal Var compensator placement problem

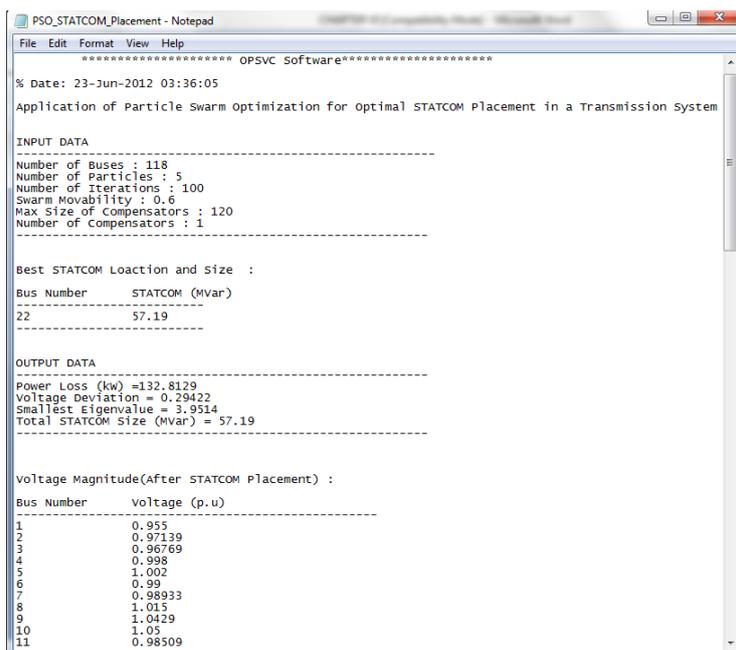


Fig.10 : Sample of the output text file created by the OPSVC

Table 1: Comparing the power flow results of the OPSVC and ETAP software for the 34 bus radial distribution system

Bus No.	$V^{OPSVC}$ (p.u)	$\delta^{OPSVC}$ (deg)	$V^{ETAP}$ (p.u)	$\delta^{ETAP}$ (deg)	$ \Delta V $	$ \Delta \delta $
1	1.0000	0.0000	1.0000	0.0000	0	0
2	0.9941	0.0527	0.9941	0.0545	4 e-05	2 e-03
3	0.9890	0.0990	0.9894	0.0997	4 e-04	7 e-04
4	0.9821	0.2133	0.9826	0.2140	5 e-04	7 e-04
5	0.9761	0.3127	0.9761	0.3138	4 e-05	1 e-03
6	0.9704	0.4075	0.9708	0.4081	4 e-04	6 e-04
7	0.9666	0.4985	0.9668	0.4997	2 e-04	1 e-03
8	0.9645	0.5484	0.9648	0.5497	3 e-04	1 e-03
9	0.9620	0.6070	0.9624	0.6085	4 e-04	2 e-03
10	0.9608	0.6351	0.9610	0.6355	2 e-04	4 e-04
11	0.9604	0.6461	0.9608	0.6449	4 e-04	1 e-03
12	0.9602	0.6494	0.9605	0.6476	3 e-04	2 e-03
13	0.9887	0.1069	0.9888	0.1067	1 e-04	2 e-04
14	0.9884	0.1140	0.9890	0.1136	6 e-04	4 e-04
15	0.9883	0.1160	0.9878	0.1147	5 e-04	1 e-03
16	0.9883	0.1161	0.9877	0.1144	6 e-04	2 e-03
17	0.9660	0.4828	0.9657	0.4816	3 e-04	1 e-03
18	0.9622	0.5458	0.9617	0.5446	5 e-04	1 e-03
19	0.9582	0.6285	0.9578	0.6273	4 e-04	1 e-03
20	0.9549	0.6954	0.9543	0.6936	6 e-04	2 e-03
21	0.9520	0.7539	0.9515	0.7537	5 e-04	2 e-04
22	0.9487	0.8331	0.9485	0.8347	2 e-04	2 e-03
23	0.9460	0.8985	0.9458	0.8986	2 e-04	1 e-04
24	0.9435	0.9603	0.9435	0.9614	2 e-05	1 e-03
25	0.9423	0.9902	0.9418	0.9904	5 e-04	2 e-04
26	0.9418	1.0017	0.9413	1.0028	5 e-04	1 e-03
27	0.9417	1.0051	0.9415	1.0061	2 e-04	1 e-03
28	0.9664	0.5041	0.9660	0.5050	4 e-04	9 e-04
29	0.9662	0.5078	0.9659	0.5090	3 e-04	1 e-03
30	0.9661	0.5106	0.9657	0.5123	4 e-04	2 e-03
31	0.9605	0.6431	0.9611	0.6437	6 e-04	6 e-04
32	0.9601	0.6511	0.9595	0.6518	6 e-04	7 e-04
33	0.9600	0.6551	0.9596	0.6552	4 e-04	6 e-05
34	0.9599	0.6564	0.9592	0.6584	7 e-04	2 e-03

### The OPSVC Software Validation

To validate the OPSVC software, the obtained power flow results are compared with the results obtained from using the electrical power systems design and analysis (ETAP) software. ETAP is a fully integrated AC and DC electrical power

system analysis tool and is used in the design, analysis, maintenance, and operation of electrical power systems (Tao et al., 2010). A comparison between the power flow results of the OPSVC and ETAP software for the 34 bus radial distribution system is shown in Table 1. The load and feeder data for the 34-bus system are given in (Sirjani et al., 2010).

From Table 1, the voltage magnitude and voltage angle of each bus computed by the OPSVC software for the 34 bus radial distribution are very close to the ETAP power flow results. The percentage difference between the voltage magnitude results of the OPSVC and ETAP software in power flow calculation is given by,

$$dif (\%) = \sum_{i=1}^n \left| \frac{V_i^{ETAP} - V_i^{OPSVC}}{V_i^{ETAP}} \right| \tag{1}$$

where  $V_i^{ETAP}$ ,  $V_i^{OPSVC}$  are the voltage magnitude of each bus computed by the ETAP and OPSVC software, respectively.

Table 2 shows the percentage differences between the power flow results of OPSVC and ETAP for the various test systems. The percentage differences have been calculated using Eq(1) . The maximum iteration number and termination tolerance are assumed as 100 and 10-5, respectively. From Table 2, it is shown that the accuracy of the power flow results computed by the OPSVC software in distribution and transmission test systems are comparable to the power flow results obtained from the ETAP software.

Table 2 : The percentage difference between the power flow results of OPSVC and ETAP for various test systems

Test System	Percentage difference (%)
10 bus distribution system	1.10
34 bus distribution system	1.32
57 bus transmission system	1.69
118 bus transmission system	2.58

### Results on the Use of OPSVC Software

To illustrate the use of the developed software tool, OPSVC, some examples for determining optimal placement and sizing of Var compensators in the test systems are considered. The application of OPSVC using the GHS algorithm for determining the optimal location and sizing of shunt capacitors in the three-phase 10 bus test system is illustrated. The 57 bus test system is also considered to illustrate the use of OPSVC in applying the IHS algorithm for optimal SVC placement and sizing in transmission systems.

**I. Example of Using OPSVC for Analysis on a Radial Distribution System**

The three-phase 10 bus test system is considered to illustrate the use of OPSVC for optimal capacitor placement and sizing in radial distribution systems by considering mutual coupling, load unbalance and harmonics. (Sirjani et al., 2011b). The GHS algorithm is selected as the optimization technique. Initially, all the required data is entered through the GUI shown in Figure 11. In the section of optimization parameters, the number of buses, number of iterations and genetic mutation probability are selected as 10, 5000 and 0.2, respectively. The studied cases are selected as; with mutual coupling and unbalance in loads. The maximum permissible THD is also selected as 5%. Then by clicking on the button “Run”, the convergence curve is plotted and then the results are shown on the right of the GUI as depicted in Figure 11.

The voltage profile of test system before and after capacitor placement is also plotted as shown in Figure 12. From the figure, it can be seen that the

voltage improvement after capacitor placement using the GHS algorithm is significant.

**II. Example of Using OPSVC for Analysis on a Transmission System**

The 57 bus test system is considered to illustrate the use of the OPSVC for optimal SVC placement and sizing in transmission systems (Sirjani et al., 2011a). . In this simulation case, the IHS algorithm is selected as the optimization technique. Initially, all the required data is entered through the GUI shown in Figure 13. The optimization parameters are selected as: number of buses =57, number of iterations = 5000, HMCR = 95%,  $PAR_{max}= 0.90$ ,  $PAR_{min}= 0.4$  and  $bw_{max}=1$  ,  $bw_{min}=10^{-6}$ . The number of SVCs is selected as 3 and the maximum permissible size of SVC is selected as 20MVar. Then by clicking on the button “Run”, the convergence curve is plotted and then the results are shown on the right of the GUI in Figure 13.

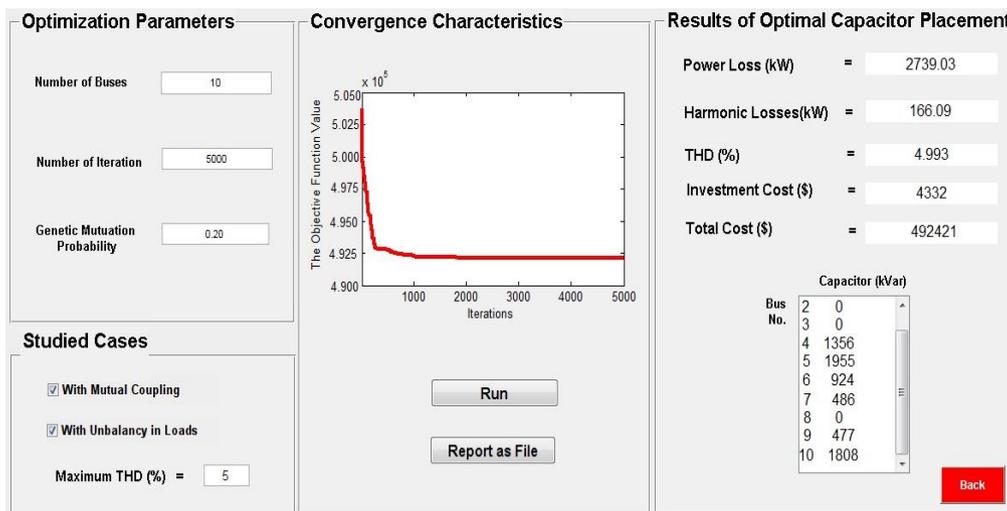


Fig.11: Output display of the GUI for optimal capacitor placement in the 10 bus distribution system using the GHS algorithm

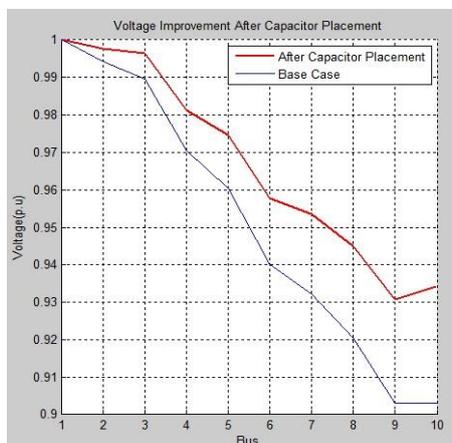


Fig.12 :Voltage improvement after optimal capacitor placement in the 10 bus distribution system plotted by the OPSVC software

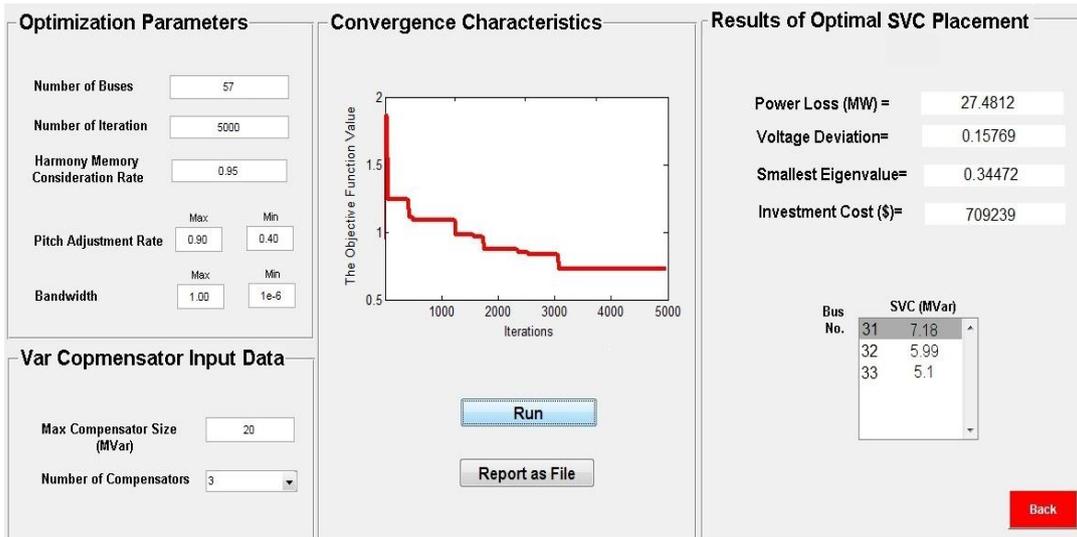


Fig.13: Output display of the GUI for optimal SVC placement in the 57 bus test system using the IHS algorithm

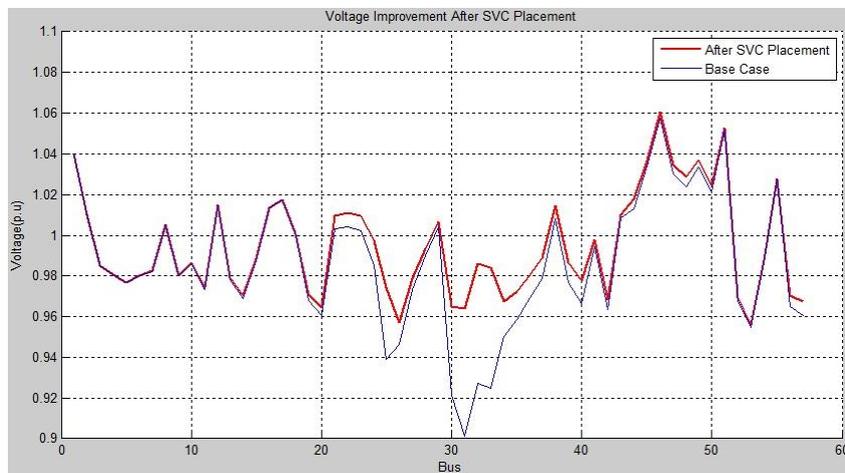


Fig.14 : Voltage improvement after SVC placement in the 57 bus test system plotted by the OPSVC software

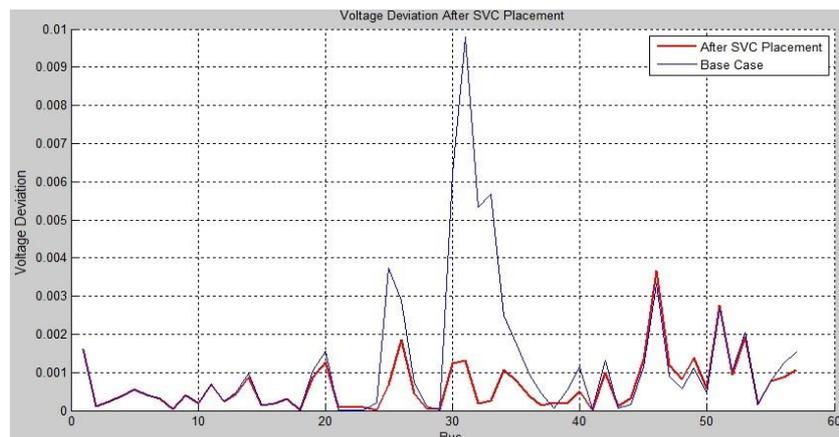


Fig.15: Voltage deviation before and after SVC placement in the 57 bus test system plotted by the OPSVC software

The voltage profile and the voltage deviation curves, before and after SVC placement are also plotted as depicted in Figure 14 and Figure 15, respectively. From the figures, it can be seen that there is a significant voltage improvement at some buses after installing the three SVCs in the 57 bus transmission system.

### Conclusions

A Matlab based software tool named as Optimal Placement of Shunt Var Compensators (OPSVC) has been developed to develop a user friendly software tool for implementing optimal sizing and placement of shunt Var compensators in distribution and transmission systems. The OPSVC

software incorporates both the developed optimization algorithms, namely, GA, PSO, HS, IHS and GHS algorithms and the backward/forward sweep power flow and radial harmonic power flow methods in an open source environment. The developed OPSVC software has been validated by checking the power flow results of the various distribution and transmission test systems with the results of the commercial ETAP software. Finally, the results of using the developed software tool, OPSVC, for optimal placement and sizing of shunt Var compensators in distribution and transmission systems have been presented.

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