CHAPTER-5

APPLICATION OF SYMBIOTIC ORGANISMS SEARCH ALGORITHM

5.1 INTRODUCTION

The progressive increase in electrical demand has been the cause for technical problems to the utility companies such as for instance, line overload, increased loss of transmission, voltage problem etc. These problems have been taken by technical team through OPF tool for planning and operation and control of the power system network. OPF is a non linear programming problem, with objective function limited by equality or inequality constrains, which optimizes the power system variables [28]. FACTS devices have proved to be a generous tool for power flow control, for the performance improvement, by not altering the generator scheduling or a change in topology. UPFC and OUPFC are the most popular devices of the FACTS devices, which can provide series and shunt compensation [65-67].

Solution to noisy, non linear optimization is obtained by many meta-heuristics [101-108]. The exploration and exploitation is done iteratively, in the solution space, assuming optimal solution. Some methods result in local optima, some global optimum. SOS algorithm is an evolutionary computing model, of recent development, is inspired by the biological interaction between the organisms in an ecosystem. SOS algorithm scores over other algorithms being simple in mathematical operations, easily codable, no tuning parameters. The algorithm has been found to be very efficient in solving optimization problems with fast convergence rate and less computational time [115,118]. In the present work, a novel approach based on SOS algorithm is proposed to solve the combined OPF and CPF problem of RPL minimization and maximization of VSL. Control variables like transformer tap positions, UPFC location and its variables are optimized with the SOS algorithm to optimize the single objective function of RPL minimization and multi-objective of RPL minimization and VSL maximization. The method adopted for optimizing single and multiple objectives are: optimize transformer taps, next UPFC locations with fixed transformer taps and finally simultaneous UPFC location and transformer taps.

The procedure is repeated for OUPFC too. The bus schemes considered are IEEE 14-bus, New England 39- bus and practical Indian 24 bus- system.

5.2 SOS ALGORITHM BASED OPTIMIZATION

Min-Yuan Cheng and Doddy Prayogo [125], developed this algorithm in the year 2014, to solve engineering design problems involving numerical optimization. The relationship between multiple different biological species is called symbiosis. The most common relationships described are:

a) Species interact beneficially- Mutualism

Example: Lichens-algae and fungi

b) One of the species is benefited, the other unchanged- Commensalism

Example: Remora fish and shark

c) Harmful to one species- Parasitism

Example: Virus and human

SOS mimics these interactions to optimize the problem within the search space. Figure 5.1 illustrates a group of symbiotic organisms in eco system.

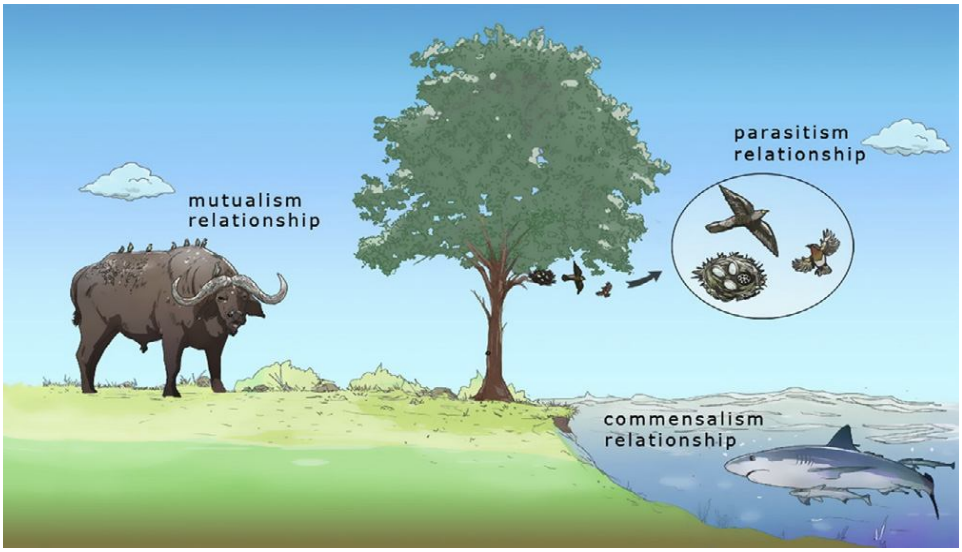


Fig. 5.1 Symbiotic organisms live together in an ecosystem.

(i) Mutualism phase

In this phase X_i , X_j are the two random organisms, which interact with in themselves so as to enhance their chances of survival. The new candidate solutions for X_i and X_j are given in equation 5.1 and 5.2.

$$X_{inew} = X_i + rand(0,1) * (X_{best} - Mutual\_Vector * BF1) \tag{5.1}$$

$$X_{jnew} = X_j + rand(0,1) * (X_{best} - Mutual\_Vector * BF2) \tag{5.2}$$

Where $Mutual - Vector = \dfrac{X_i + X_j}{2}$ (5.3)

The rand (0, 1) is a vector of random numbers. The organism can be partially or fully benefited from the interaction and the benefit factor BF1 and BF2 are in the range 1-2. Equation 5.3 represents the mutual vector, giving the relationship between X_i and X_j. The value (X_{best} –Mutual_Vector) reflects the efforts by the organism to increase survival. All the better values, replace the original solutions.

(ii) Commensalism phase

Similar to mutualism phase two random organisms X_i and X_j from the ecosystem are allowed to interact in commensalism phase. In this interaction organism X_i benefits from the interaction, but organism X_j neither benefit nor suffers from the relationship. The new candidate solution of X_i is calculated, which is modelled in equation 5.4 as

$$X_{inew} = X_i + rand(-1,1) * (X_{best} - X_j) \tag{5.4}$$

The benefit advantage in this case is provided by (X_{best} –X_j) in which the organism X_j provides maximum benefit to organism X_i in terms of survival.

(iii) Parasitism phase

In parasitism phase, one of the randomly selected organisms from the ecosystem X_i acts as a “Parasite-Vector”. The duplicating organism X_i creates the parasite _vector and, modified by a random number. The newly formed parasite fights for survival with the organism X_j. If X_j has lesser fitness than the parasite, then the parasite kills the organism X_j and takes its place in the ecosystem.

5.2.1 Merits and Demerits of SOS Algorithm

- SOS and other population based algorithms like GA, DE, PSO, MBA, CS etc., are similar in many characteristics, with their iterative performance on a collection of candidate solutions to achieve the global solution.
- SOS algorithm does not procreate unlike in GA, DE, but adapts through individual interactions.
- SOS differs with other algorithms by using three different strategies of mutualism, commensalism and parasitism.
- The strategy of SOS which modifies candidate solution, after taking the difference between best and average solution is called mutualism. The advantage of exploring new search space is utilized, when the organisms are separated by a wide space. The values of the interacting individuals are updated simultaneously.
- Commensalism in SOS utilizes the best solution as the point of reference and exploits points nearer to it. The speed of convergence is thus enhanced.
- Parasitism is a mutation operator , unique to SOS, the trial mutation vector, competes randomly with other excepting its parent, having the following advantages:

  a) Complete solution is modified.

  b) The modified dimensions represent the characteristics of local search.

  c) Because of randomization, the solutions are widely spread in the solution space.

5.2.2. Pseudo code of SOS algorithm [125]

The basic steps of the SOS algorithm can be expressed in the following pseudo-code:

Define objective function $f(x)$; $x=(x_1, x_2, x_3,\ldots,x_d)$ *%d* is dimension of the problem

Initialize an ecosystem of n organisms with random solutions

While (t<Max Generation)

for i=1: n % n is the number of organism

Find the best organism X_{best} in the ecosystem

%Mutualism phase

Randomly select one organism X_j, *where* $X_j \neq X_i$

Determine mutual relationship vector (*Mutual _ Vector*) and benefit vector (*BF*)

Modify organisms X_i and X_j using (5.1) and (5.2)

If modified organisms give better fitness evaluation than previous, then update them in Ecosystem

%Commensalism phase

Randomly select one organism X_j, where $X_j \neq X_i$

Modify organism X_i with the help of X_j using (5.4)

If the modified organism gives better fitness evaluation, then update it in ecosystem

%Parasitism phase

Randomly select one organism X_j, where $X_j \neq X_i$

Generate *parasite _ Vector* form organism X_i

If *parasite_ vector* gives better fitness value than X_j, then replace it with

Parasite _ vector

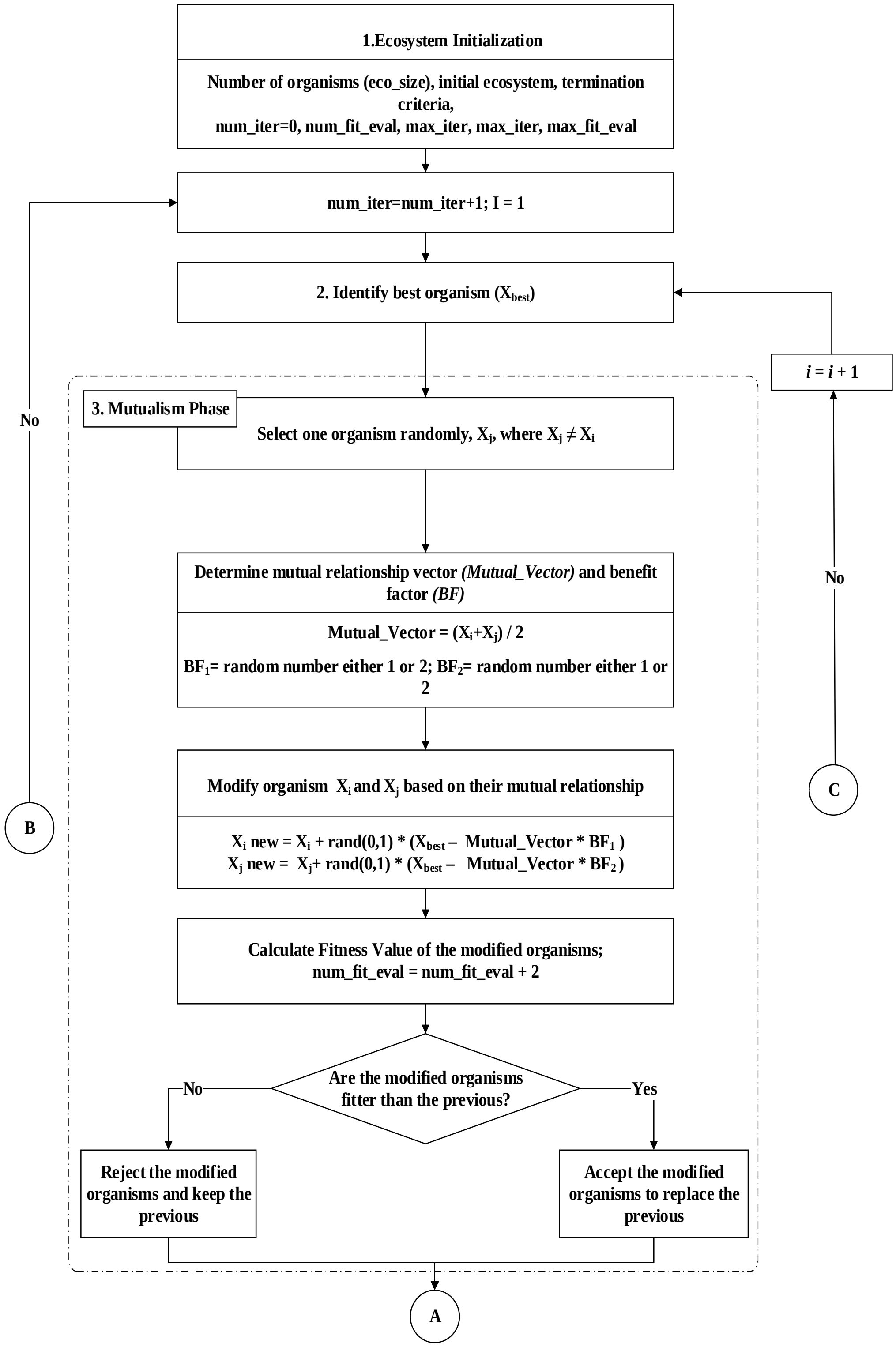
end for

The global best solution is saved as optimal solution

end while

5.2.3 General flow chart of SOS Algorithm

The Flow chart of the SOS algorithm is shown in figure 5.2



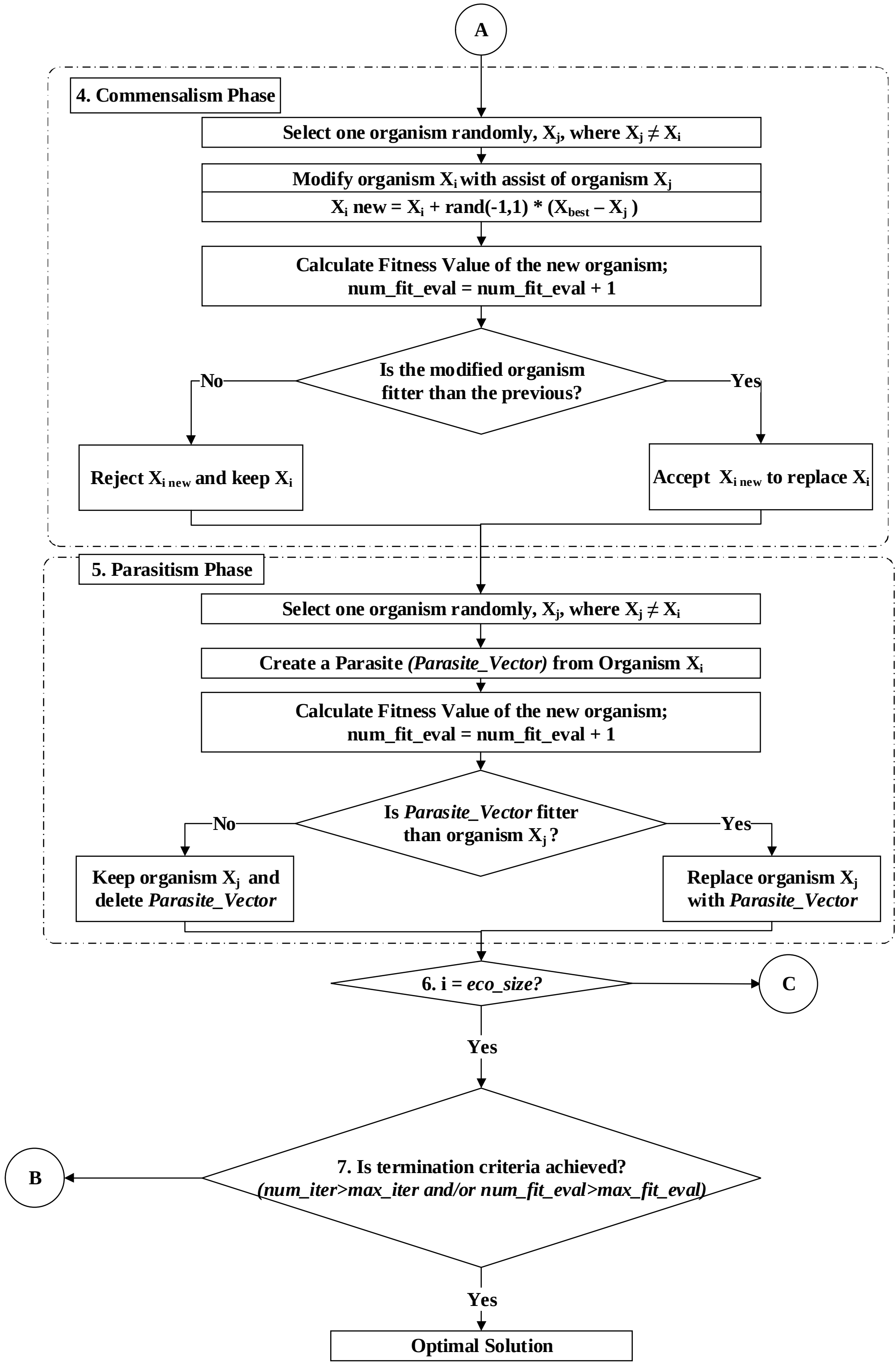


Fig. 5.2 Flow chart for SOS algorithm based optimization

5.3. IMPLEMENTATION OF SOS ALGORITHM

The application of SOS algorithm technique for the solution of Optimal power flow problem and combined OPF-CPF problem is explained below:

The different steps of the SOS are as follows:

Step1: Initialization of Ecosystem

(i) Number of organisms=40

(ii) Maximum iterations=30

(iii) Iteration counter I=0

Step2: Create the random population for the ecosystem. Measure the fitness of the organisms by using fitness function

Step3: Identify the best solution (X_{best})

Step4: Increment the iteration counter $I = i+1$

Step5: Mutualism Phase

Choose the two random organisms X_i and X_j from the ecosystem for interaction. Obtain new solutions $X_{i\ new}$ and $X_{j\ new}$ from the interaction using equations (5.1) & (5.2) and compare them with the original solutions. Replace them if the solutions are better.

Step6: Commensalism phase

Choose a random organism X_j from the eco system to interact with organism (X_i). The obtained new solution from the interaction $X_{i\ new}$ as in equation (5.4) is competed against X_i and whichever has the better fitness deserves the place in the ecosystem.

Step7: Parasitism Phase

Obtain a parasite vector (X_i) and parasite randomly from the ecosystem. Determine the fitness function and replace the original solution if the parasite has better fitness.

Step8: Calculate the best solution (X_{best}) for the current ecosystem.

Step9: If the maximum number of iterations is reached go to step10, else go to step 4.

Step10: Display the results for the solution X_{best}

5.3.1 Flow chart of optimization strategy with SOS Algorithm

The flow chart of optimization strategy with SOS algorithm is shown in figure 5.3.

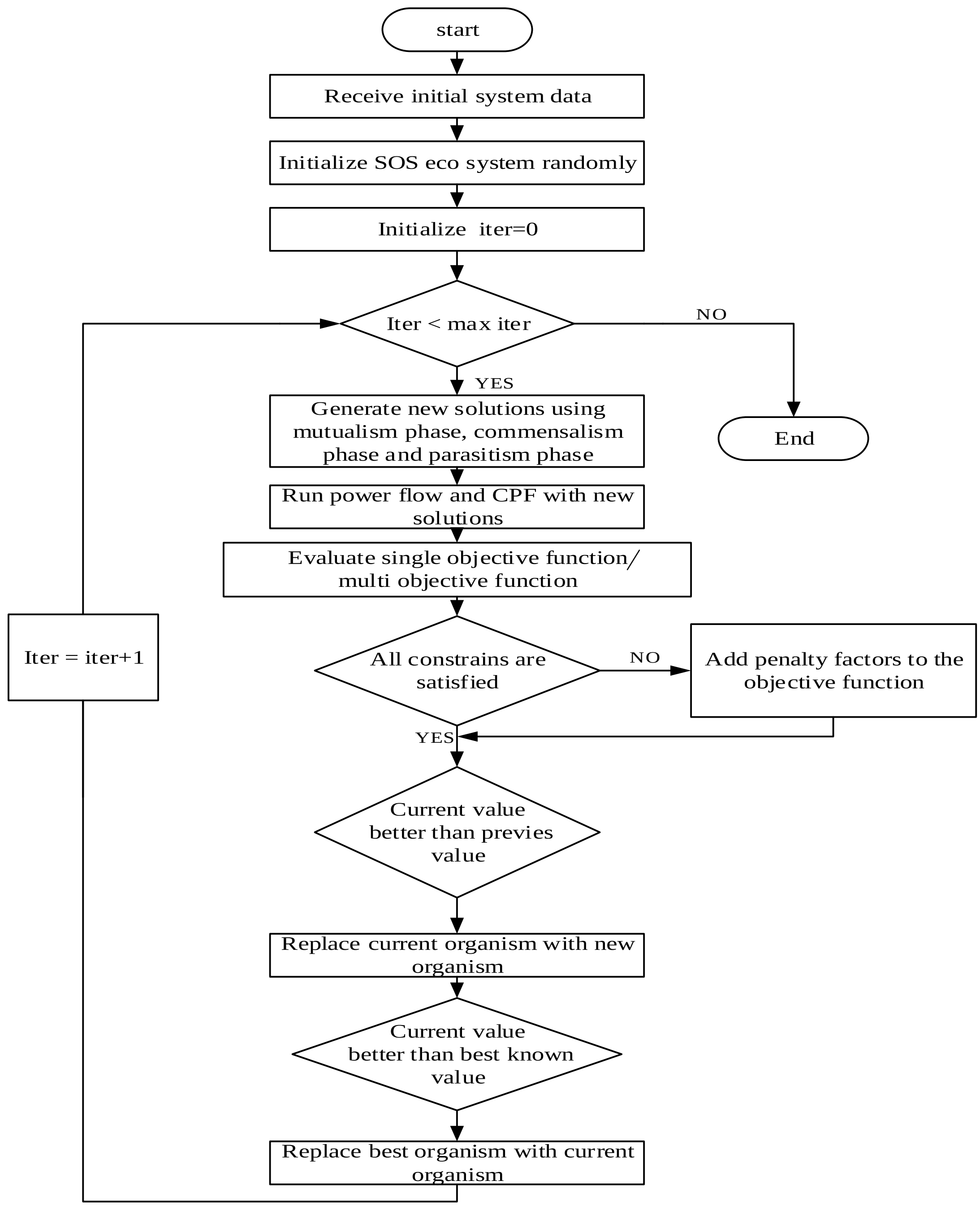


Fig. 5.3 Optimization strategy with SOS algorithm

5.4 SIMULATION RESULTS AND DISCUSSION

The effectiveness of the proposed SOS method to solve optimization problem for both single and multi-objective cases has been demonstrated using IEEE 14-bus system [123] and New England 39-bus system [124] and practical Indian 24 bus system [57]. A software program has been developed in the MATLAB and run on core i5, 2.5 GHz and 4GB RAM computer. The details of the test systems are given below:

Test system 1: IEEE 14 -bus system

The single line diagram of The IEEE 14 bus test system shown in figure A.1 of appendix A. The IEEE 14 bus test system comprises of 5 generator buses, 9 load buses, and 20 transmission lines. Of this bus 1 is slack bus, lines 4-7, 4-9 and 5-6 have discrete operating valued tap changers. Buses 9 and 14 are with discrete valued shunt compensations. Power flow is solved for the base case with nominal taps and found the value of RPL as 0.13394p.u. The value of VSL obtained with CPF technique is 0.93.

Test system 2: New England 39- bus system

New England 39 bus test system consists of 10generator buses, 12 transformers and 46 transmission lines. Single line diagram is given in figure B.1.of Appendix B. Buses from 30 to 39 are generator buses with 31 as the slack bus and remaining are the load buses. The transformers T_1 to T_{12} are located in the lines 2-30, 10-32, 12-11, 12-13, 19-33, 19-20, 20-34, 22-35, 23-36, 25-37, 29-38, 31-6 respectively. Power flow is run for the base case to find RPL and using CPF technique. For this test system with nominal values of taps, the RPL is 0.4378 p.u and VSL is 0.81.

Test system 3: 24- bus practical Indian system

The single line diagram of the practical Indian 24 bus test system is shown in figure C.1 of appendix C. Practical Indian 24 bus test system consists of 4 generator buses, 11 transformers and 27 transmission lines. Buses from 1 to 4 are generator buses with 1 as the slack bus and remaining are the load buses. The transformers T_1

to $T_{11}$are located in the lines 15-1, 17-2, 24-3, 21-4, 16-5, 19-6, 20-7, 14-8, 23-9, 18-10, 22-13, respectively. Power flow is run for the base case to find RPL and the VSL is obtained using CPF technique. For this test system with nominal values of taps, the RPL is 0.64642p.u and VSL is 0.0703.

The SOS based optimization method is developed in MATLAB environment for optimization of both single and multi-objective problems considering, the following cases:

Case1: Optimization with only transformer taps

Case 2: Sequential optimization of UPFC location and its parameters keeping the Optimized transformer taps fixed.

Case 3: Simultaneous optimization of UPFC location and its parameters along with taps Next OUPFC is considered and the optimization is carried out in the same way.

Case 4: Sequential optimization of UPFC location and its parameters keeping the optimized transformer taps fixed

Case 5: Simultaneous optimization of OUPFC location and its parameters along with taps.

The simulation parameters of SOS algorithm considered for the test cases are shown in table 5.1

Table 5.1 Parameters of SOS algorithm

S.NO	Parameters	Quantity
1	Number of organisms	40
2	No. of iterations	30
3	Benefit Factor (BF1)	1
4	Benefit Factor(BF2)	2

5.4.1 Case 1: Optimization with only transformer taps

5.4.1.1 Case 1.1: Optimization of only RPL (single objective case)

In this case the transformer taps are optimized with SOS technique for single objective case. The optimized transformer taps along with RPL and VSL obtained with proposed technique are given in tables 5.2, 5.3, and 5.4 for IEEE 14 bus, New England 39 bus and practical Indian 24 bus system respectively. From the results it is clear that the RPL reduced to 0.6443 % (from 0.13394 p.u. to 0.133077), 0.8382 %(from 0.43780 to 0.4011) and 16.8388 (from 0.64642 to 0.53757) for IEEE 14- bus, New England 39- bus and practical Indian 24- bus system respectively compared to base case. In the single objective case VSL is not included in the fitness function. With the optimized taps the CPF is run for estimating the voltage stability limit in the single objective case and found to be 1.020, 0.870, and 0.142540 for the test systems considered.

5.4.1.2 Case 1.2: Optimization of both RPL and VSL (multi-objective case)

When both RPL and VSL are optimized in the multi-objective case, the fitness function is modified. The reciprocal of VSL is added to the real power loss and the optimization is carried out with SOS technique. The optimized transformer taps along with RPL and VSL obtained with proposed technique are given in tables 5.2, 5.3 and 5.4 for the test systems considered. From the results it is seen that the VSL is improved but RPL is increased marginally with SOS technique for all the test systems. Even RPL is increased slightly; the overall multi-objective function that is the sum of real power loss and reciprocal of VSL is reduced compared to single objective case. RPL has increased by a margin of 0.4606 % (from 0.133077 p.u to 0.13369 p.u.), 0.2493 % (from0.4011 p.u. to 0.4021 p.u.) and 0.5506% (form 0.53757 to 0.54053) and VSL has improved to 5.8823 % (form 1.02 to 1.08), 17.2413 % (from 0.870 to 1.02), and 1.7959 % (from 0.142540 to 0.145100) for IEEE 14, New England 39 and Indian 24 bus test systems respectively compared to single objective case. But the combined fitness function obtained with SOS in multi-objective case has reduced to 5.4745 %(from 9.9369 to 9.3929), 14.2014 %(from 11.8953 to 10.206) and 1.5993 %(from 7.5531 to 7.4323) for the test systems considered compared to single objective case. This shows that the SOS is able to optimize both RPL and VSL simultaneously for stable and secure operation of power system.

Table 5.2 Results of IEEE 14 bus test system for case study 1

Control variable settings	Optimization of RPL only (Single objective case)	Optimization of both RPL and VSL (multi-objective case)
	SOSS	SOSM
T_1 (4-7)	1.10	1.15
T_2 (4-9)	0.90	0.95
T_3 (5-6)	1.00	1.05
RPL, p.u.	0.133077	0.13369
VSL	1.020	1.080
Combined fitness function (W1*RPL+W2*1/VSL)	9.9369	9.3929

Table 5.3 Results of New England 39 bus test system for case study 1

Control variable settings	Optimization of RPL only (Single objective case)	Optimization of both RPL and VSL (multi-objective case)
	SOSS	SOSM
T_1 (2-30)	1.10	1.05
T_2 (10-32)	1.15	1.15
T_3 (12-11)	1.00	1.00
T_4 (12-13)	1.00	0.95
T_5 (19-33)	1.15	1.10
T_6(19-20)	1.00	1.00
T_7 (20-34)	1.15	1.10
T_8 (22-35)	1.15	1.10
T_9(23-36)	1.10	1.00
T_{10}(25-37)	1.10	1.05
T_{11} (29-38)	1.15	1.05
T_{12} (31-6)	1.00	1.05
RPL, (p.u.)	0.4011	0.4021
VSL	0.870	1.020
Combined fitness function (W1*RPL+W2*1/VSL)	11.8953	10.2060

Table 5.4 Results of the practical Indian 24- bus system for case study 1

Control variable settings	Optimization of RPL only (Single objective case)	Optimization of both RPL and VSL (multi-objective case)
	SOSS	SOSM
T1 (15-1)	1.0375	1.0250
T2 (17-2)	1.0250	1.0250
T3 (24-3)	1.0250	1.0250
T4 (21-4)	1.0500	1.0500
T5 (16-5)	0.9125	0.9125
T6 (19-6)	0.9250	0.9125
T7 (20-7)	0.9250	0.9250
T8 (14-8)	0.9625	0.9000
T9 (23-9)	0.9625	0.9875
T10 (18-10)	0.9625	0.9625
T11 (22-13)	0.9750	0.9125
RPL(p.u.)	0.53757	0.54053
VSL	0.142540	0.145100
Combined fitness function (W1*RPL+W2*1/VSL)	7.5531	7.4323

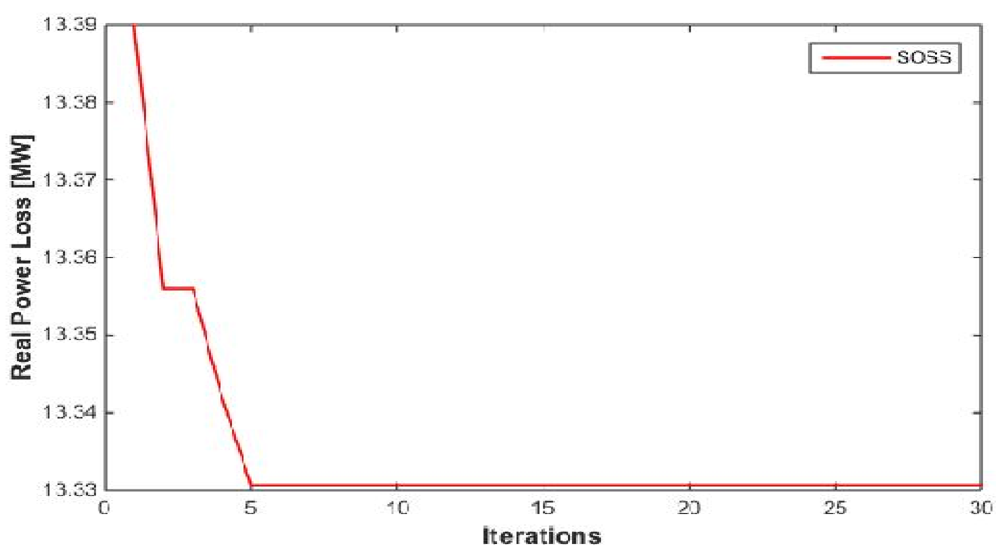


Fig. 5.4 Convergence characteristic of IEEE14- bus system for case study 1.1

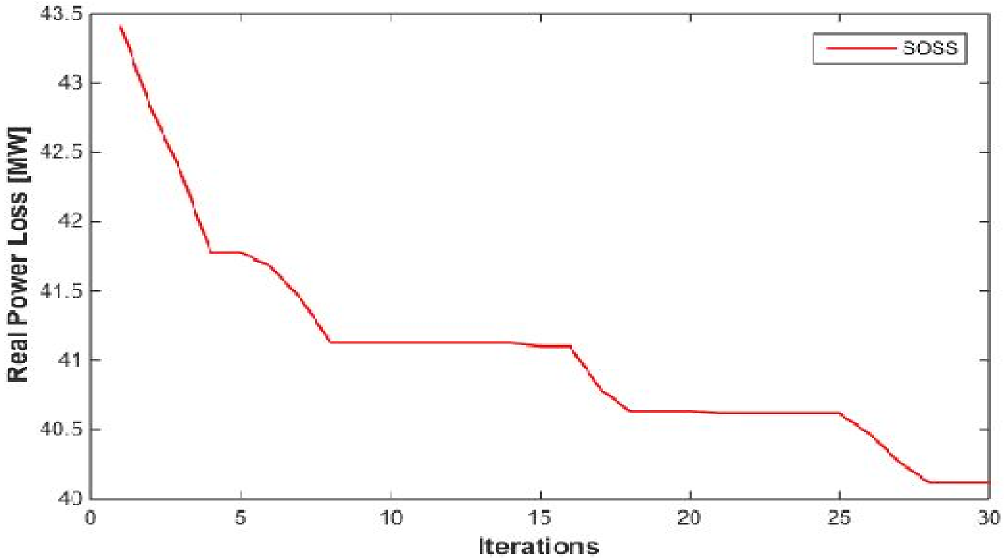


Fig. 5.5 Convergence characteristic of New England 39-bus system for case study 1.1

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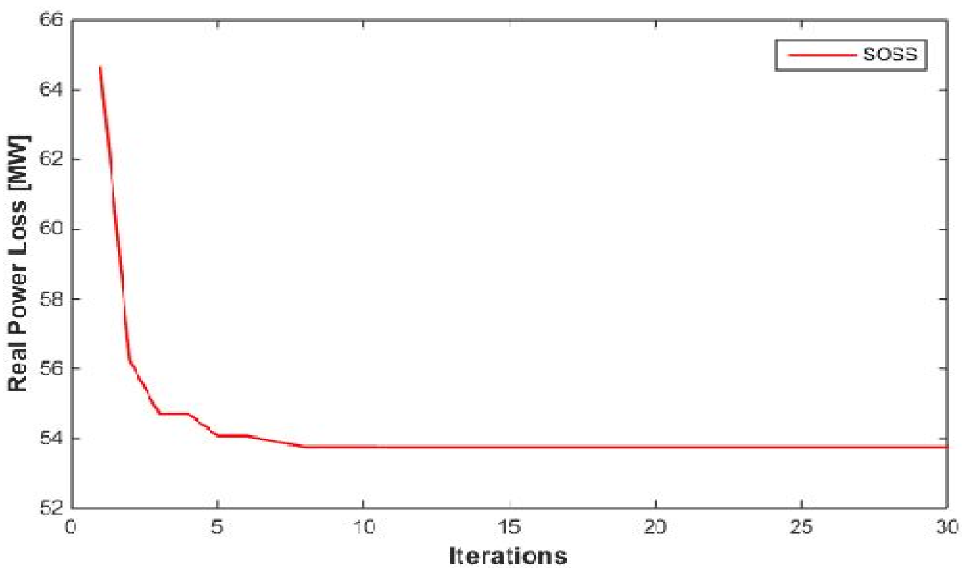

Fig. 5.6 Convergence characteristic of practical Indian 24-bus system for case study 1.1

The figures 5.4 to 5.6 show the single objective RPL minimization, depicting the convergence. From the results it is found that the proposed SOS performs better in terms of loss minimization, computational time, convergence speed and accuracy. The solution started with higher value but finally reached minimum value in the objective values and it clearly shows that global solution is reached with minimum number of iterations

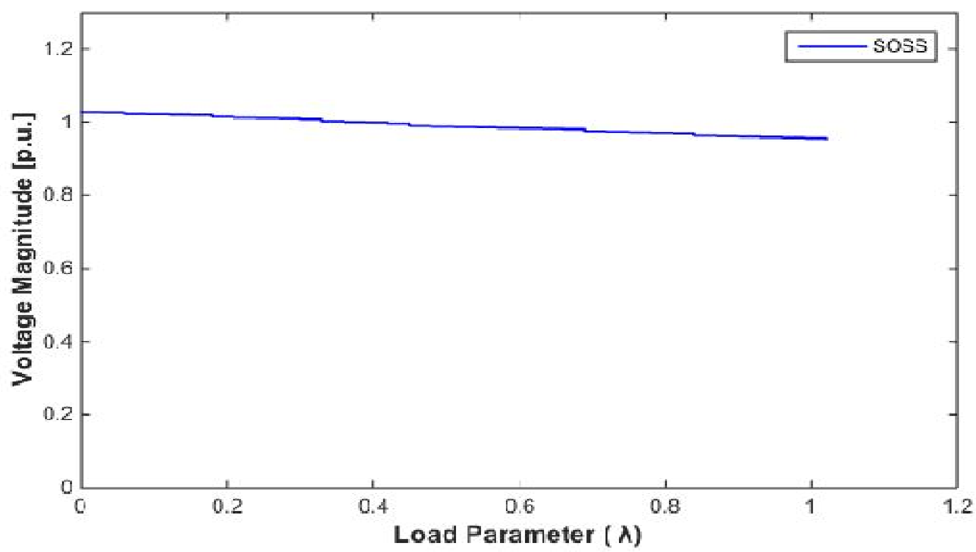

Fig. 5.7 P-V curve of the weakest bus of IEEE14- bus system with SOSS for case study 1.1

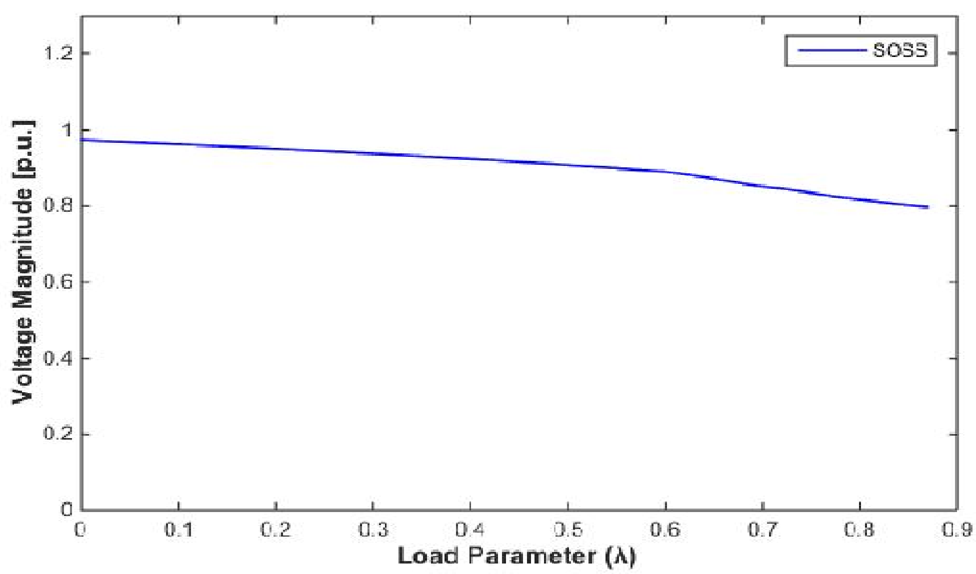

Fig. 5.8 P-V curve of the weakest bus of New England 39- bus system with SOSS for case study 1.1

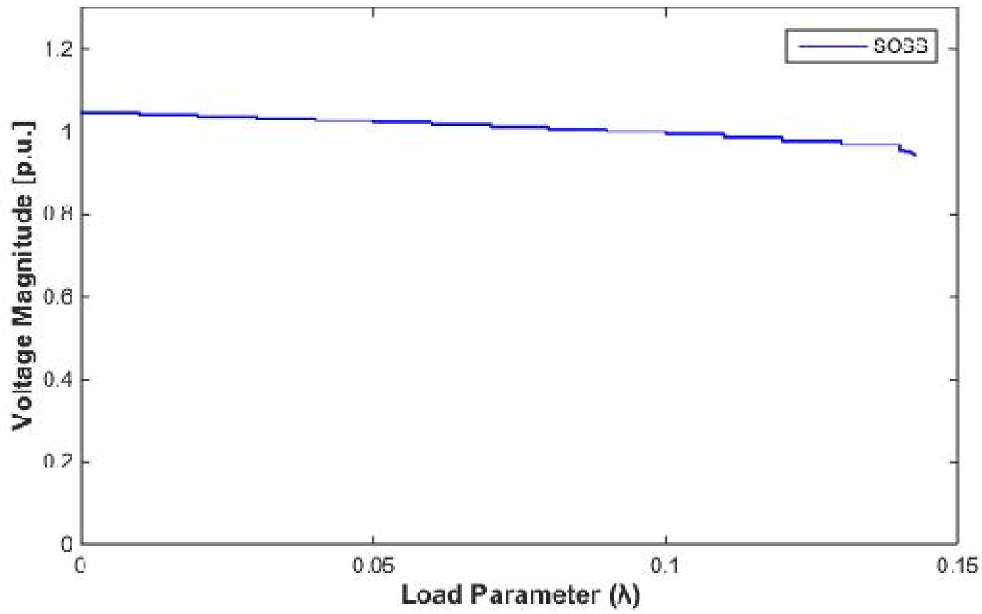

Fig. 5.9 P-V curve of the weakest bus of Indian 24-bus system with SOSS for case study 1.1

Figures 5.7, 5.8 and 5.9 show the p-v curves for weakest bus of the test systems considered, are for the SOS with a single objective under the optimal control variables of the transformer settings excluding VSL in the fitness function. The CPF for VSL resulted in values 1.02, 0.870 and 0.142540 for the test systems considered.

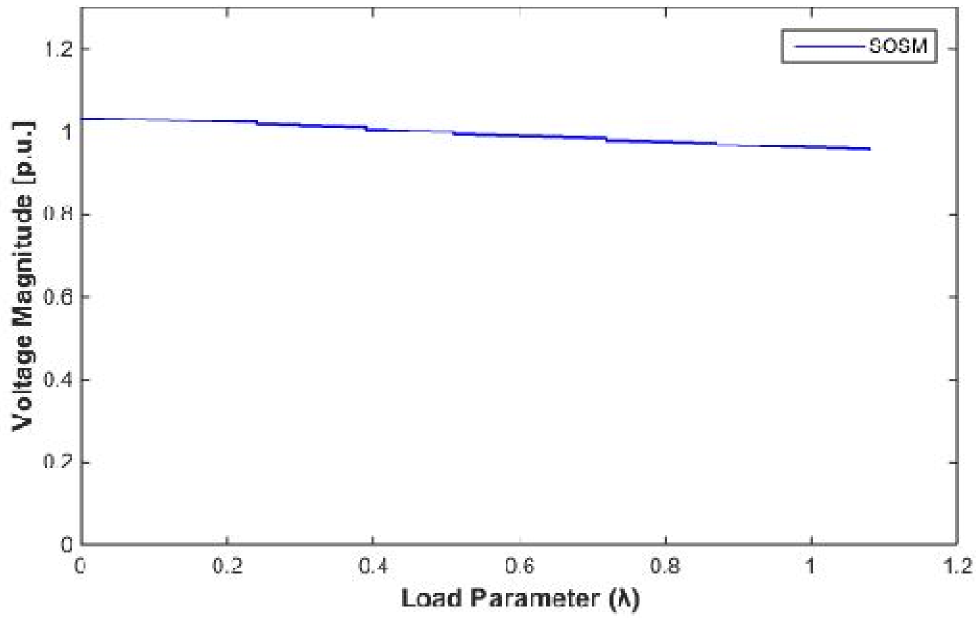

Fig. 5.10 P-V curve of weakest bus of IEEE 14- bus system with SOSM for case study 1.2

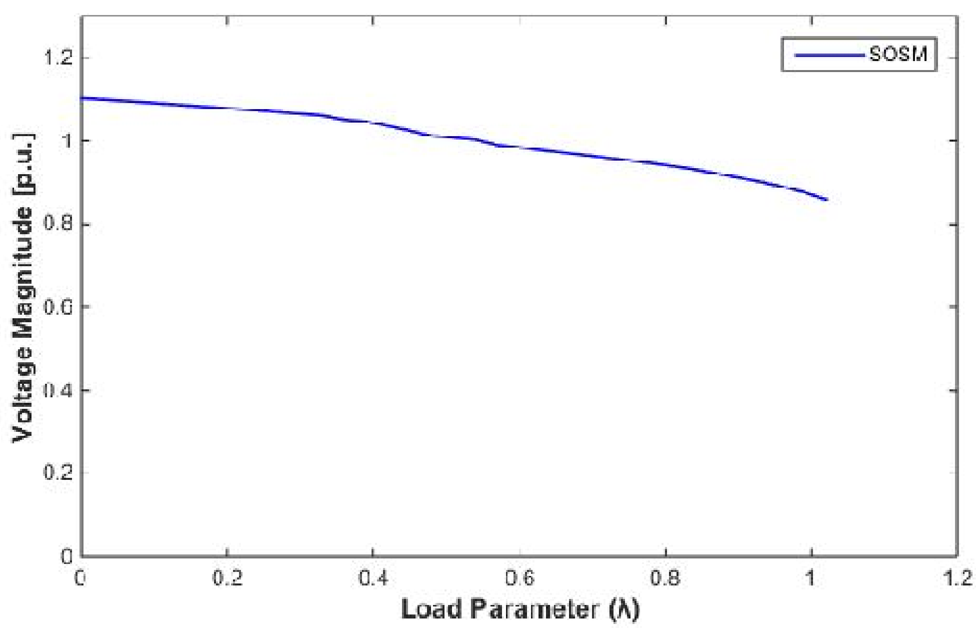

Fig. 5.11 P-V curve of weakest bus of 39- bus system with SOSM for case study 1.2

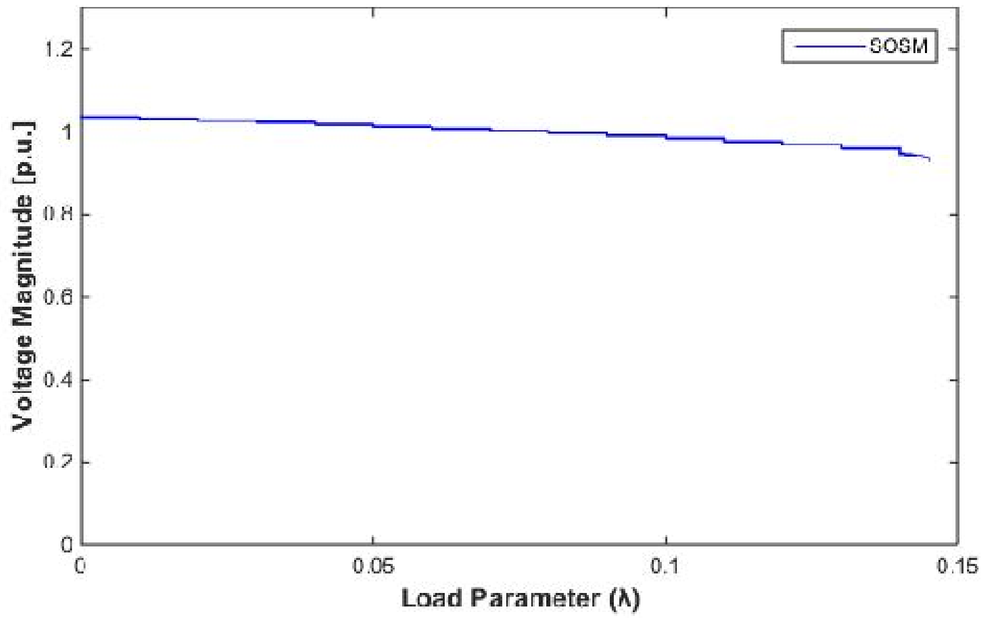

Fig. 5.12 P-V curve of weakest bus of 24-bus system with SOSM for case study 1.2

Figures 5.10, 5.11 and 5.12 show the p-v curves of weakest bus of IEEE 14 bus system, New England 39- bus system and Indian 24 bus system with optimal transformer tap settings as control variables obtained using SOS for multi-objective case. It is clear from the results that VSL has improved to 16.129 %(from 0.93 to 1.08), 25.9259 % (from 0.81 to 1.02), and 106.4011 %(from 0.0703 to 0.145100) for IEEE 14, New England 39 and Indian 24 bus test systems respectively compared to base case . Also It is observed from the figures that the VSL has improved to 5.8823 % (form 1.02 to 1.08), 17.2413 % (from 0.870 to 1.02), and 1.7959 % (from 0.142540 to 0.145100) for the test systems considered compared to single objective case. It can be concluded that voltage stability margin was improved using CPF, to ensure the feasibility of the optimal transformer tap settings for secure operation of power system.

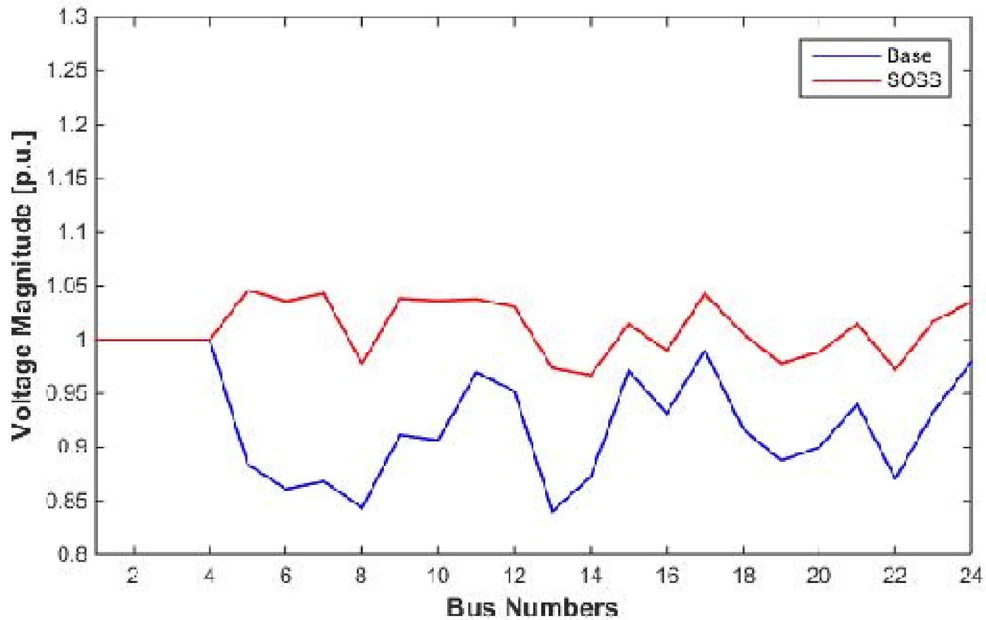

Fig. 5.13 Voltage profiles of practical Indian 24-bus system with SOSS for case study 1.1

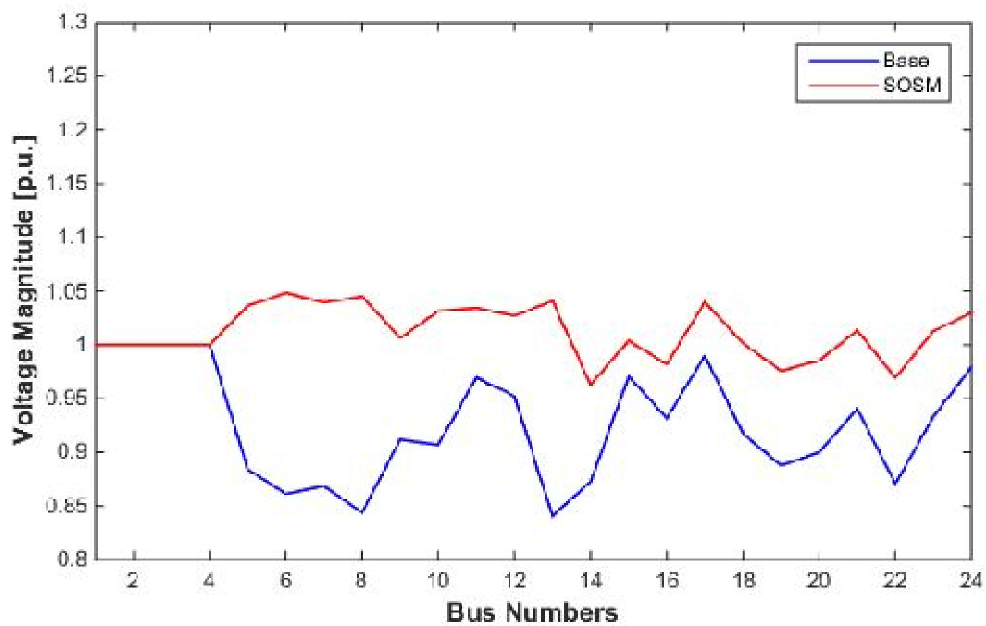

Fig. 5.14 Voltage profiles of practical Indian 24- bus system with SOSM for case study 1.2

Figures 5.13 and 5.14 show the voltage profiles corresponding to the base case PF and with SOS of all buses of the test system considered. It is clear from the figures that SOS has helped to improve voltage profile in all the load buses.

5.4.2 Case 2: Sequential optimization of UPFC location and its parameters keeping the optimized transformer taps fixed

5.4.2.1 Case 2.1: Optimization of only RPL (Single objective case)

With the optimized transformer taps fixed (obtained from case 1.1), the UPFC variables are then optimized using the proposed SOS technique so that objective function could still be reduced. The optimized UPFC location and its parameters along with RPL and VSL obtained with proposed technique are given in tables 5.5, 5.6 and 5.7 for the test systems considered. The power injection model as discussed in chapter- 3 is used for modelling the UPFC. For IEEE 14 bus system only 7 lines are considered for connecting the UPFC as the remaining 13 lines consists of transformers and feeding generator powers to the network. For New England 39 bus system 32 lines are considered for connecting the UPFC as the remaining 14 lines consists of transformers and feeding generator powers to the network. Similarly for practical Indian 24 bus system 16 lines are considered for connecting the UPFC as the remaining 11 lines consists of transformers and feeding generator powers to the network. It is clear from the results that with the incorporation of UPFC device, the RPL has reduced to 22.526 %(from 0.133077 to 0.1031), 12.739 % (from 0.4011 to 0.3500), 10.1121 %(from 0.53757 to 0.48321) compared to case 1.1 for IEEE 14 bus, New England 39 bus and practical Indian 24 bus system respectively . It is seen that when more nonlinear equipment like UPFC is inducted into the system, the fitness function has successfully converged with SOS. This shows the potentiality of the proposed algorithm in solving the non liner optimization problem particularly the RPL minimization problem. In the single objective case VSL is not included in the fitness function. With the optimized taps the CPF is run for estimating the voltage stability limit in the single objective case and found to be 1.02, 0.96 and 0.1400 for the test systems considered.

5.4.2.2 Case 2.2: Optimization of both RPL and VSL (multi-objective case)

When both RPL and VSL are optimized in the multi-objective case, the fitness function is modified. The reciprocal of VSL is added to the real power loss and the optimization is carried out with SOSM technique. The optimized UPFC parameters along with RPL and VSL obtained with proposed technique are given in tables 5.5, 5.6 and 5.7 for IEEE 14, New England 39 and Indian 24 bus test systems respectively. From the results it is seen that the VSL is improved but RPL is increased marginally with SOSM technique for all the test systems. Even RPL is increased slightly; the overall multi-objective function that is the sum of real power loss and reciprocal of VSL is reduced compared to single objective case. Here RPL has increased by a margin of 6.7701% (from 0.1031 p.u to 0.1108 p.u.), 0.8285 % (from0.3500 p.u. to 0.3529 p.u.) and 0.0515% (form 0.48321 p.u. to 0.50810 p.u.) and VSL has improved to 8.8235 % (form 1.02 to 1.11), 9.375 % (from 0.96 to 1.05), and 17.0714 % (from 0.1400 to 0.1639) for IEEE 14, New England 39 and Indian 24 bus test systems respectively compared to single objective case. But the combined fitness function obtained with FAM has reduced to 7.9450 %(from 9.9070 to 9.11988), 8.2653 %(from 10.7666 to 9.8767) and 13.3309 %(from 7.6260 to 6.60938) for IEEE 14 bus, New England 39 bus and practical Indian 24 bus systems respectively compared to single objective case. Also it is clear that when UPFC is inducted to the system the overall combined fitness function is further reduced to 2.90666 % (from 9.3929 to 9.11988), 3.2265 %(from10.2060 to 9.8767) and 11.0721 % (from 7.4323 to 6.609388) for the test systems considered compared to case 1.2. It is found that with SOSM, the UPFC parameters can be optimized that the system could be loaded beyond double, its nominal loading before a voltage collapse could occur for all the test systems. So SOS is best succeeded in reducing the combined objective of loss minimization and VSL maximization.

Table 5.5 Results of IEEE 14- bus test system for case study 2

Control variable Settings	Optimization of RPL only (Single objective case)	Optimization of both RPL and VSL (multi-objective case)
	SOSS	SOSM
UPFC series injected voltage, V_{se} , p.u.	0.030	0.05
UPFC series injected voltage angle, $\boldsymbol{\delta_{se}}$, rad	1.48909	1.4500
UPFC location	4-5	7-9
RPL, p.u.	0.1031	0.1108
VSL	1.020	1.110
Combined fitness function (W1*RPL+W2*1/VSL)	9.9070	9.11988

Table 5.6: Results of New England 39- bus system for case study 2

Control variable Settings	Optimization of RPL only (Single objective case)	Optimization of both RPL and VSL (multi-objective case)
	SOSS	SOSM
UPFC series injected voltage, V_{se} ,(p.u.)	0.007732	0.0100
UPFC series injected voltage angle, $\boldsymbol{\gamma}$, (rad)	0.960410	0.922958
UPFC location	21-22	17-18
RPL, (p.u.)	0.3500	0.3529
VSL	0.9600	1.0500
Combined fitness function (W1*RPL+W2*1/VSL)	10.7666	9.8767

Table 5.7 Results of the practical Indian 24- bus system for case study 2

Control variable Settings	Optimization of RPL only (Single objective case) SOSS	Optimization of both RPL and VSL (multi-objective case) SOSM
UPFC series injected voltage, V_{se} ,(p.u.)	0.072859	0.162500
UPFC series injected voltage angle, γ ,(rad)	1.692566	4.625000
UPFC location	24-23	22-23
RPL (p.u.)	0.48321	0.50810
VSL	0.14000	0.163900
Combined fitness function (W1*RPL+W2*1/VSL)	7.6260	6.609388

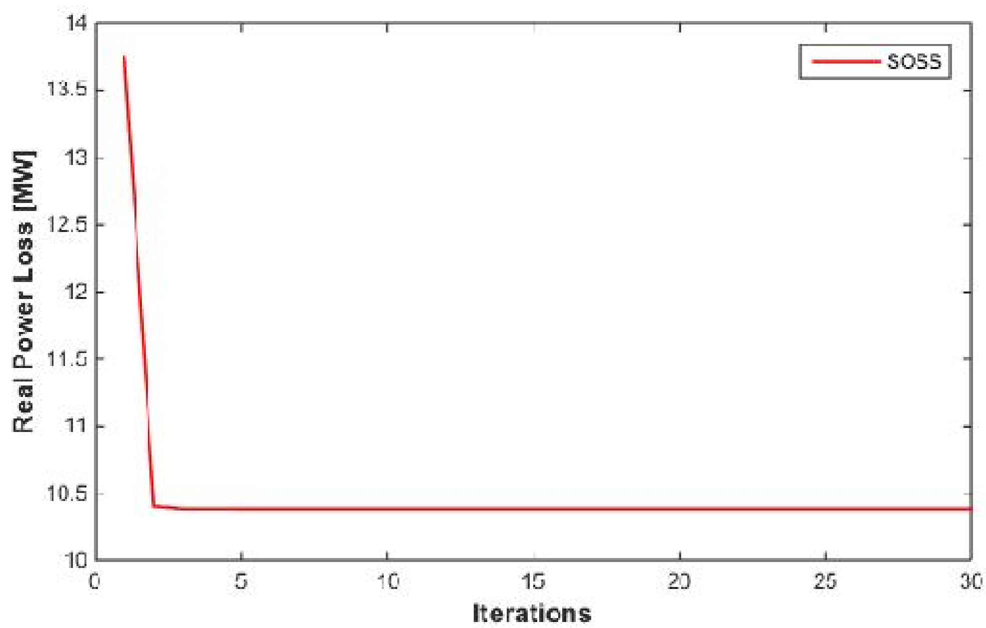

Fig. 5.15 Convergence characteristic of IEEE 14- bus system for case study 2.1

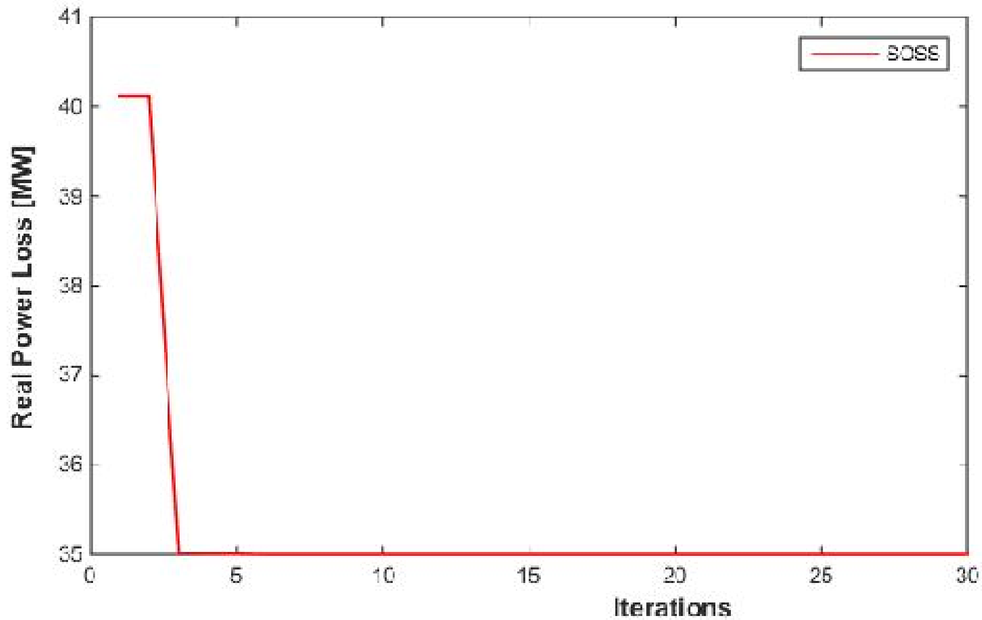

Fig. 5.16 Convergence characteristic of New England 39- bus system for case study 2.1

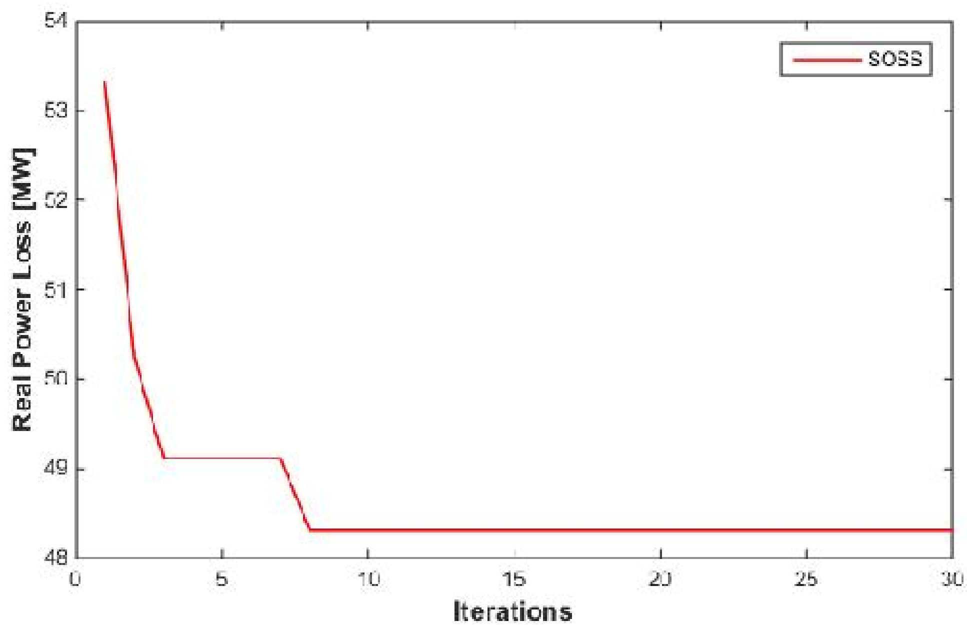

Fig. 5.17 Convergence characteristic of practical Indian 24- bus system for case study 2.1

The figures 5.15 to 5.17 show the single objective RPL minimization, depicting the convergence. From the results it is found that the proposed SOS with UPFC performs better in terms of loss minimization, convergence speed and accuracy. The solution started with higher value but finally reached further minimum value in the objective values and it clearly shows that global solution is reached with minimum number of iterations. Analyzing the simulation results, from the convergence point of view, it is clear that with the incorporation of UPFC, it can be noted that the performance of SOS with UPFC is better than the performance of SOS without UPFC (case 1.1).

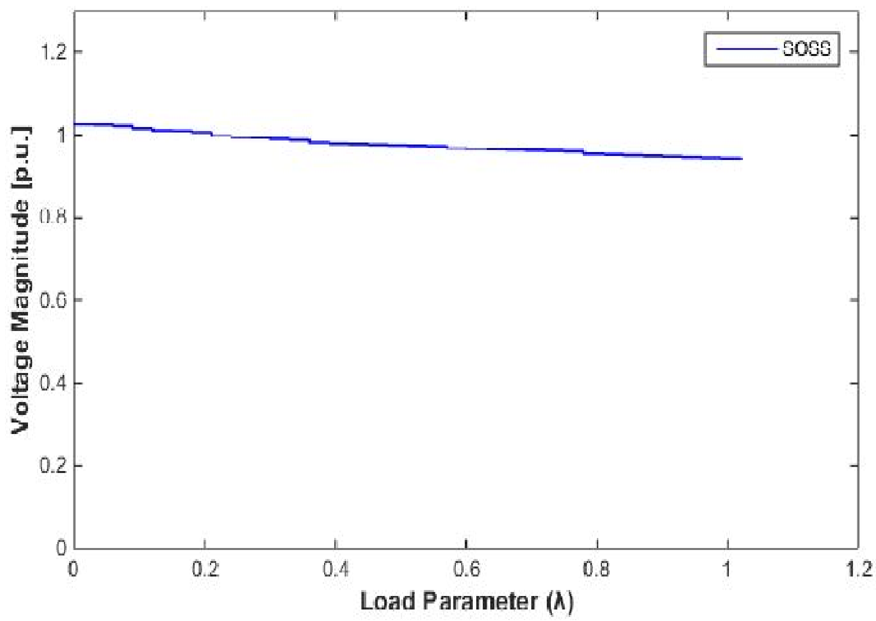

Fig. 5.18 P-V curve of the weakest bus of IEEE 14 bus system with SOSS for case study 2.1

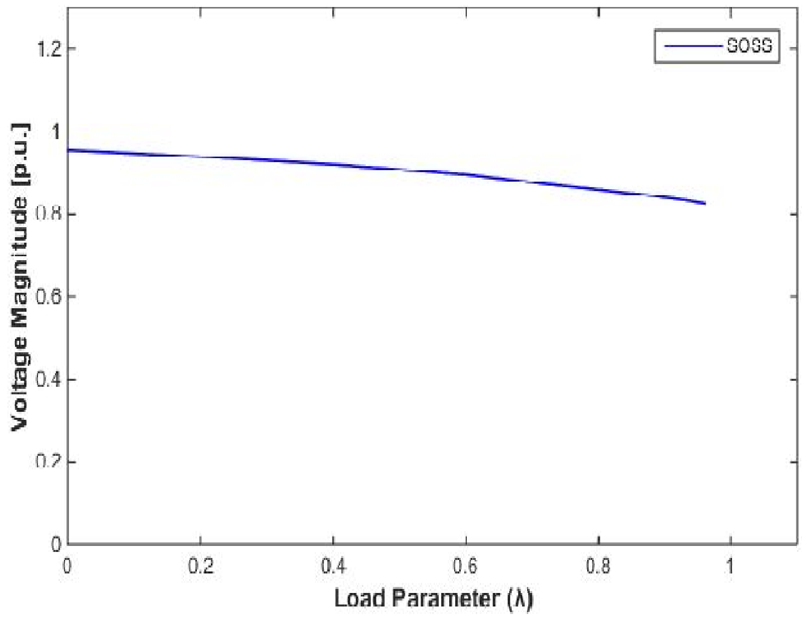

Fig. 5.19 P-V Curve of the weakest bus of the New England 39- bus system with SOSS for case study 2.1

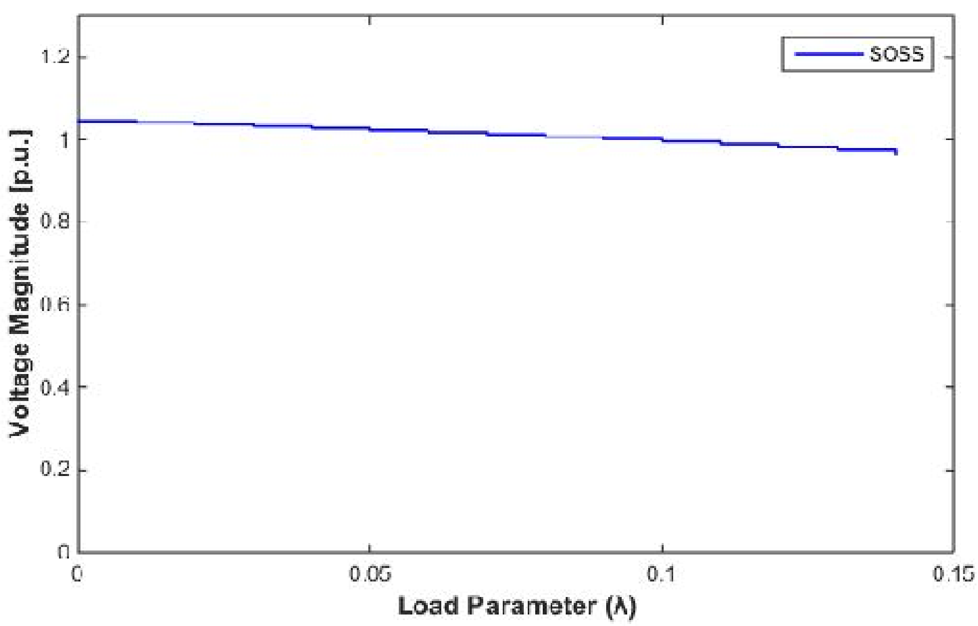

Fig. 5.20 P-V Curve of the weakest bus of the practical Indian 24- bus system with SOSS for case study 2.1

Figures 5.18, 5.19 and 5.20 show the p-v curves for weakest bus of the test systems considered, are for the SOS with a single objective under the optimal control variables of the UPFC location and its parameters excluding VSL in the fitness function . The CPF for VSL resulted in values 1.02, 0.96 and 0.1400 for the test systems considered.

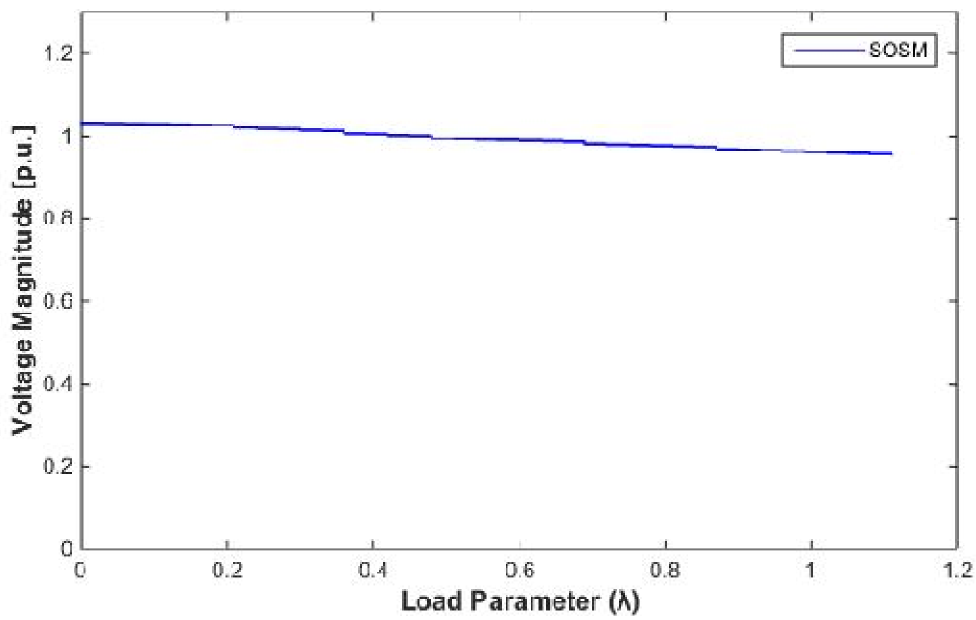

Fig. 5.21 P-V curve of the weakest bus of IEEE 14- bus system with SOSM for case study 2.2

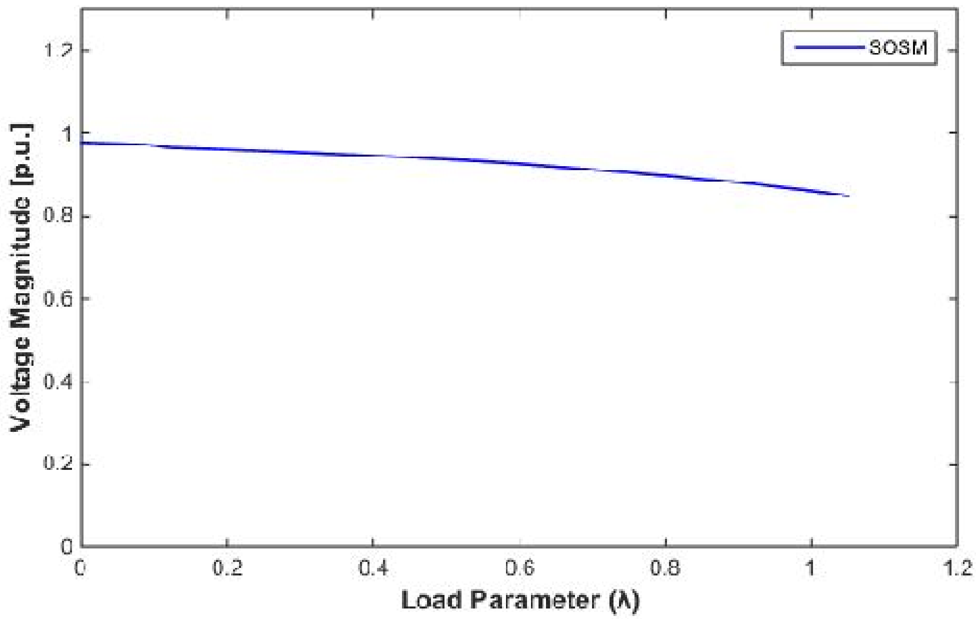

Fig. 5.22 P-V Curve of the weakest bus of the New England 39-bus system with SOSM for case study 2.2

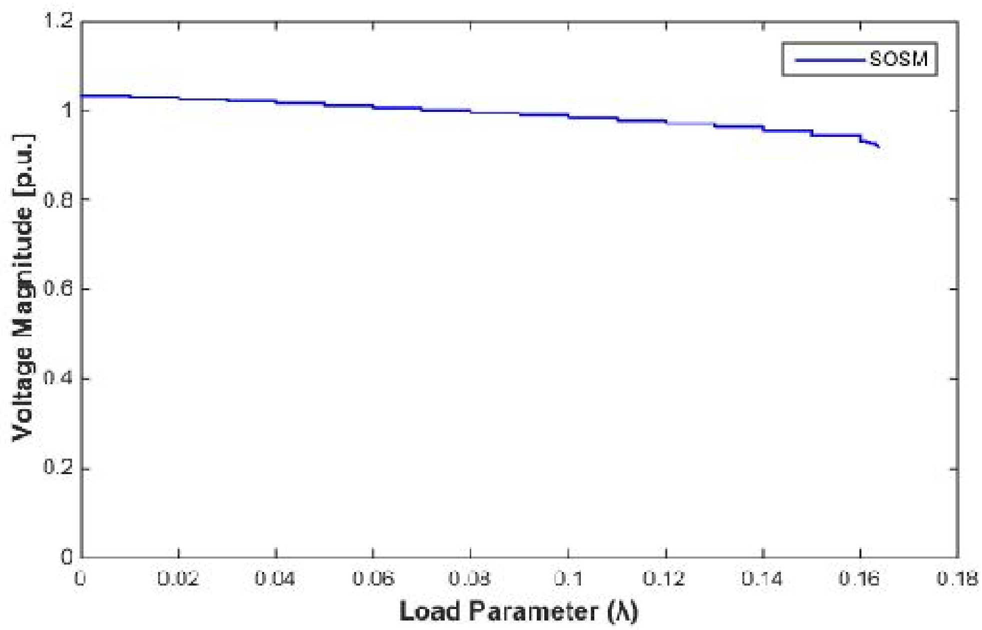

Fig. 5.23 P-V Curve of the weakest bus of the practical Indian 24- bus system with SOSM for case study 2.2

Figures 5.21, 5.22 and 5.23 show the p-v curves of weakest bus of IEEE 14 bus system, New England 39 bus system and Indian 24 bus system when variables are sequentially optimized with SOS for multi-objective case. It is clear from the results that VSL has improved to 19.3548 %(from 0.93 to 1.11), 29.6296 % (from 0.81 to 1.05), and 133.1436 %(from 0.0703 to 0.1639) for IEEE 14, New England 39 and Indian 24 bus test systems respectively compared to base case . Also It is observed from the figures that the VSL has improved to 8.8235 % (form 1.02 to 1.11), 9.375 % (from 0.96 to 1.05), and 17.0714 % (from 0.1400 to 0.1639) for IEEE 14, New England 39 and Indian 24 bus test systems respectively compared to single objective case. It can be concluded that voltage stability margin was further improved using CPF, to ensure the feasibility of the optimal position and parameter settings of UPFC for secure operation of power system.

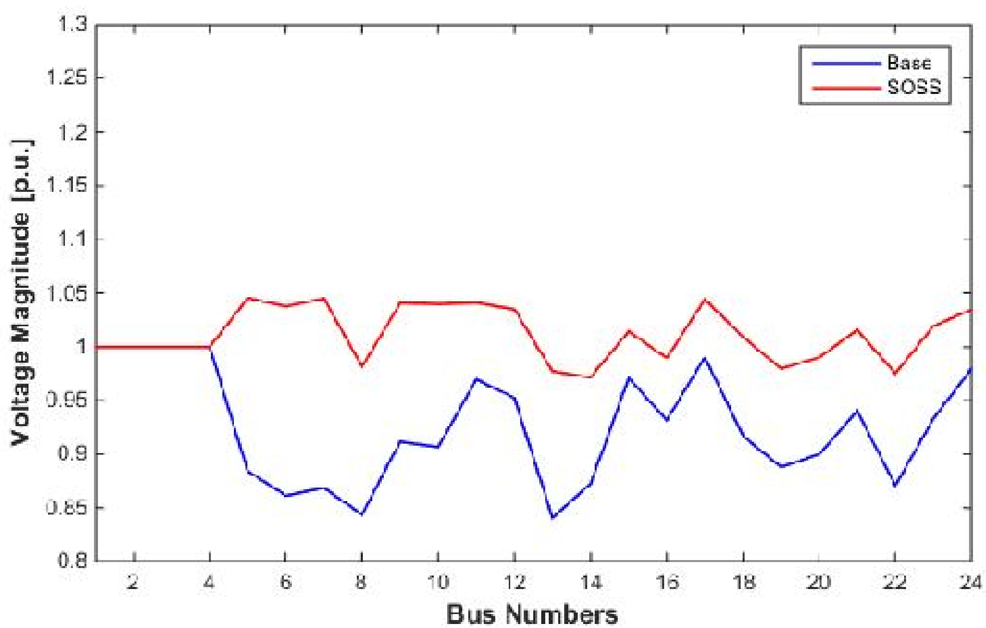

Fig. 5.24 Voltage profiles of practical Indian 24- bus system with SOSS for case study 2.1

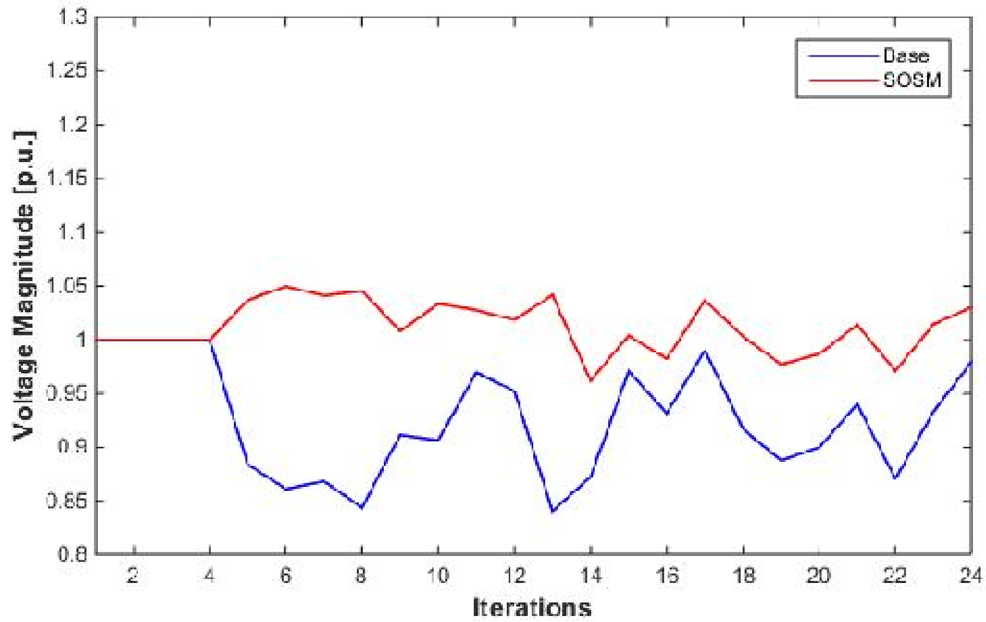

Fig. 5.25 Voltage profiles of practical Indian 24- bus system with SOSM for case study 2.2

Figures 5.24 and 5.25 show the voltage profiles corresponding to the base case PF and with SOS of all buses of the test system considered. It is clear from the figures that SOS has helped to improve voltage profile in all the load buses which leads to further reduction of losses and improvement in stability margin. Similar characterises can be observed for the test systems considered.

5.4.3 Case 3: Simultaneous Optimization of UPFC location and parameters along with taps

5.4.3.1 Case 3.1: Optimization of only RPL (single objective case)

Simultaneous optimization of UPFC location and its variables along with the transformer taps with SOSS could still reduce the objective function. For optimizing with the SOSS, the number of variables now becomes 6 i.e., 3 transformer tap positions, and 3 UPFC variables, 15, i.e., 12 transformer tap positions, and three UPFC variables 14, i.e,11 transformer tap positions, and 3 UPFC variables for the test systems considered. The optimized transformer taps, UPFC location and its parameters along with RPL and VSL obtained with proposed technique are given in tables 5.8, 5.9 and 5.10 for IEEE 14 bus, New England 39 bus and practical Indian 24 bus system respectively. It is clear from the results that, the RPL has reduced furthermore to 4.4422 %(from 0.1031 to 0.09852), 5.7142 % (from 0.3500 to 0.3300), 6.8727 %(from 0.48321 to 0.4500) compared to case 2.1 for IEEE 14 bus, New England 39 bus and practical Indian 24 bus system respectively when variables are simultaneously optimized . With the optimized taps the CPF is run for estimating the voltage stability limit in the single objective case and found to be 1.14, 0.930 and 0.14356 for the test systems considered.

5.4.3.2 Case 3.2: Optimization of both RPL and VSL (multi-objective case)

When both RPL and VSL are optimized in the multi-objective case, the cost function is modified. The reciprocal of VSL is added to the real power loss and the optimization is carried out with SOSM technique. The optimized transformer taps, UPFC parameters along with RPL and VSL obtained with proposed technique are given in table 5.8, 5.9 and 5.10 for IEEE 14, New England 39 bus and practical Indian 24 bus test systems respectively. From the results it is seen that the VSL is improved but RPL is increased marginally with SOSM technique for all the test systems. Even RPL is increased slightly; the overall multi-objective function that is the sum of real power loss and reciprocal of VSL is reduced compared to single objective case. Here RPL has increased by a margin of 0.9439% (from 0.09852 to 0.09945), 6.0606 % (from 0.3300 to 0.3500) and 0.6 % (form 0.4500 to 0.45270) and VSL has improved to 7.7947 % (form 1.14 to 1.23), 19.3548 % (from 0.93 to 1.11), and 24.0108 % (from 0.14356 to 0.17803) for IEEE 14, New England 39 and practical Indian 24 bus test systems respectively compared to single objective case. But the combined fitness function obtained with SOSM has reduced to 7.2252 %(from 8.87044 to 8.22953), 14.8133 %(from 11.0826 to 9.4409) and 18.1502 %(from 7.4157 to 6.06973) for IEEE 14 bus, New England 39 bus and practical Indian 24 bus systems respectively compared to single objective case. Also it is clear that when variables are simultaneously optimized the overall combined fitness function is further reduced to 9.7627 % (from 9.11988 to 8.22953), 4.4124 %(from 9.8767 to 9.4409), 8.1650 %(6.609388 to 6.06973) for IEEE 14 bus, New England 39 bus and practical Indian 24 bus systems respectively compared to case 2.2. It is found that with SOSM, when variables are simultaneously optimized that the system could be more loaded before a voltage collapse could occur for all the test systems. So SOS is best succeeded in reducing the combined objective of loss minimization and VSL maximization.

Table 5.8 Results of IEEE 14 bus system for case study 3

Control variable Settings	Optimization of RPL only (Single objective case)	Optimization of both RPL and VSL (multi-objective case)
	SOSS	SOSM
T_1 (4-7)	0.95	0.95
T_2 (4-9)	0.95	0.90
T_3 (5-6)	1.05	1.05
UPFC series injected voltage, V_{se} , (p.u.)	0.05	0.050
UPFC series injected voltage angle, γ , (rad)	1.300	1.450
UPFC location	9-10	9-10
RPL,(p.u.)	0.09852	0.09945
VSL	1.140	1.230
Combined fitness function (W1*RPL+W2*1/VSL)	8.87044	8.22953

Table 5.9: Results of the New England 39 bus test system for case study 3

Control variable Settings	Optimization of RPL only (Single objective case)	Optimization of both RPL and VSL (multi-objective case)
	SOSS	SOSM
T_1 (2-30)	1.00	1.05
T_2 (10-32)	1.15	1.05
T_3 (12-11)	0.90	1.10
T_4 (12-13)	0.95	1.05
T_5 (19-33)	1.05	1.05
T_6(19-20)	1.05	0.95
T_7 (20-34)	1.00	1.05
T_8 (22-35)	1.05	1.15
T_9(23-36)	1.00	0.95
T_{10}(25-37)	1.00	1.05
T_{11} (29-38)	1.05	1.00
T_{12} (31-6)	1.05	1.10
UPFC series injected voltage, V_{se} ,(p.u.)	0.01510	0.01028
UPFC series injected voltage angle, γ , (rad)	0.7321	0.961468
UPFC location	13-14	22-23
RPL, (p.u.)	0.3300	0.3500
VSL	0.9300	1.110
Combined fitness function (W1*RPL+W2*1/VSL)	11.0826	9.4409

Table 5.10: Results of practical Indian 24 bus system for case study 3

Control variable Settings	Optimization of RPL only (Single objective case)	Optimization of both RPL and VSL (multi-objective case)
	SOSS	SOSM
T1 (15-1)	0.9375	0.9500
T2 (17-2)	1.0375	1.0375
T3 (24-3)	1.0000	1.0500
T4 (21-4)	1.0375	1.0500
T5 (16-5)	0.9500	0.9875
T6 (19-6)	1.0000	0.9250
T7 (20-7)	0.9375	0.9375
T8 (14-8)	1.0250	0.9125
T9 (23-9)	0.9750	1.0125
T10 (18-10)	1.0000	0.9875
T11 (22-13)	0.9875	0.9750
UPFC series injected voltage, Vse ,(p.u.)	0.018669	0.126850
UPFC series injected voltage angle, γ, (rad)	1.091488	1.339458
UPFC location	15-24	12-14
RPL (p.u.)	0.45000	0.45270
VSL	0.14356	0.17803
Combined fitness function (W1*RPL+W2*1/VSL)	7.4157	6.06973

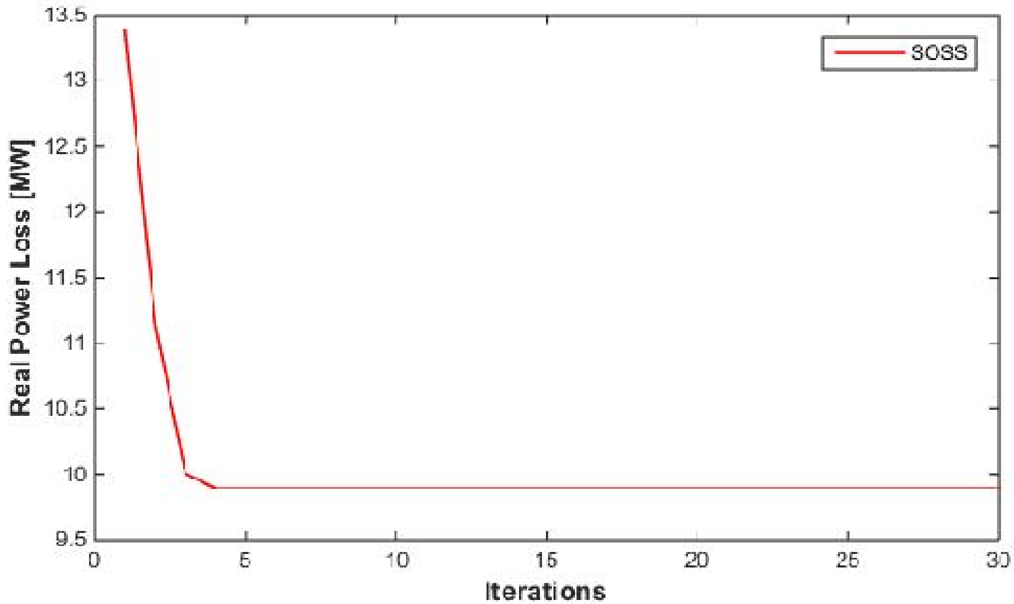

Fig. 5.26 Convergence characteristic of IEEE 14- bus system for case study 3.1

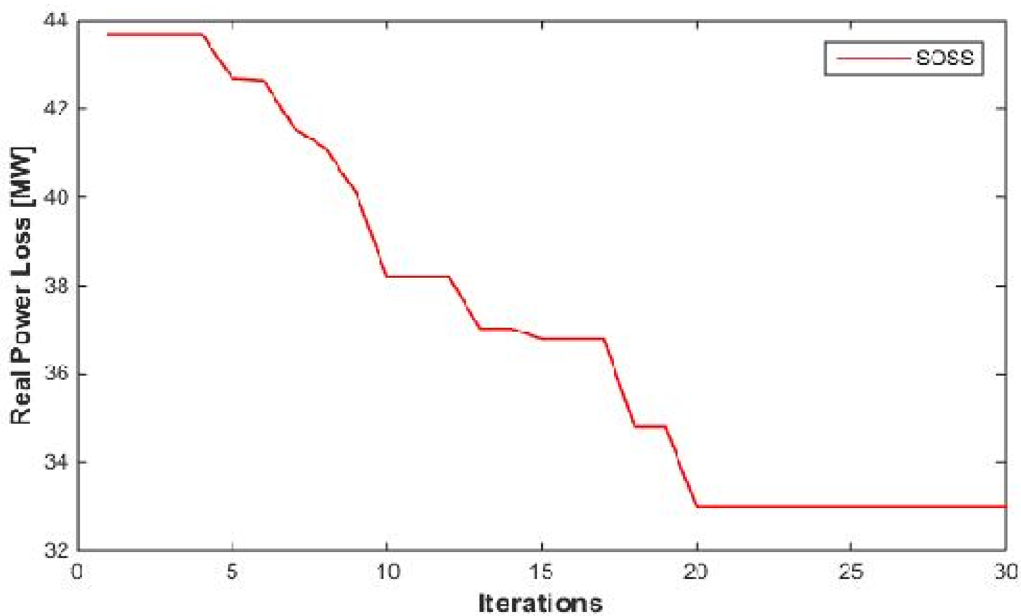

Fig. 5.27 Convergence characteristic of New England 39-bus system for case

study 3.1

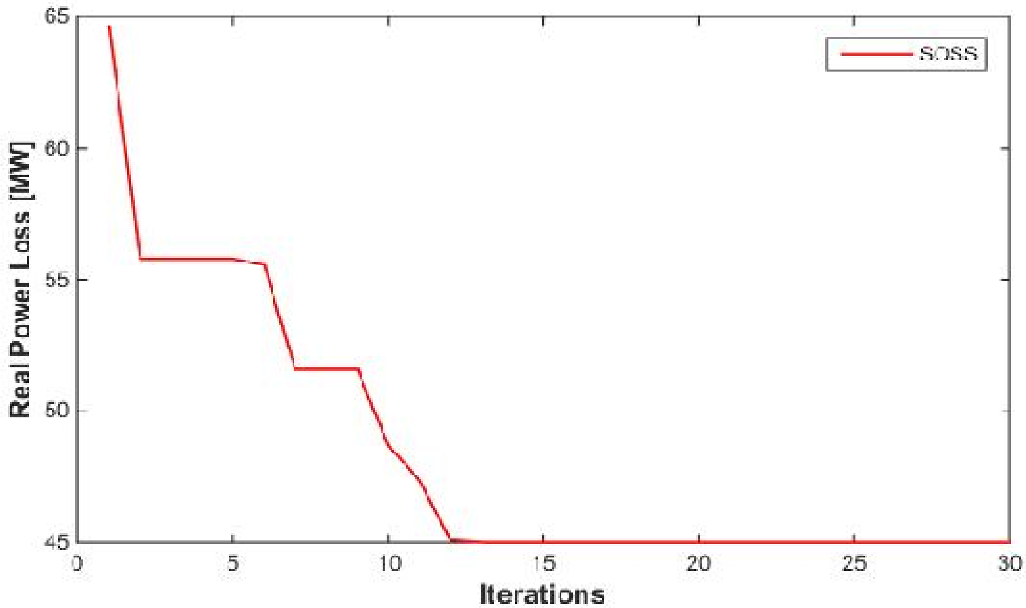

Fig. 5.28 Convergence characteristic of practical Indian 24 bus system for case study 3.1

The figures 5.26 to 5.28 show the single objective RPL minimization, depicting the convergence. From the results it is found that the proposed algorithm performs better in terms of loss minimization, convergence speed and accuracy. The solution started with higher value but finally reached further minimum value in the objective values and it clearly shows that global solution is reached with minimum number of iterations. Analyzing the simulation results, from the convergence point of view, it is clear that when variables are simultaneously optimized, it can be noted that the performance of SOS is better than the performance of case 1.1 and case 1.2.

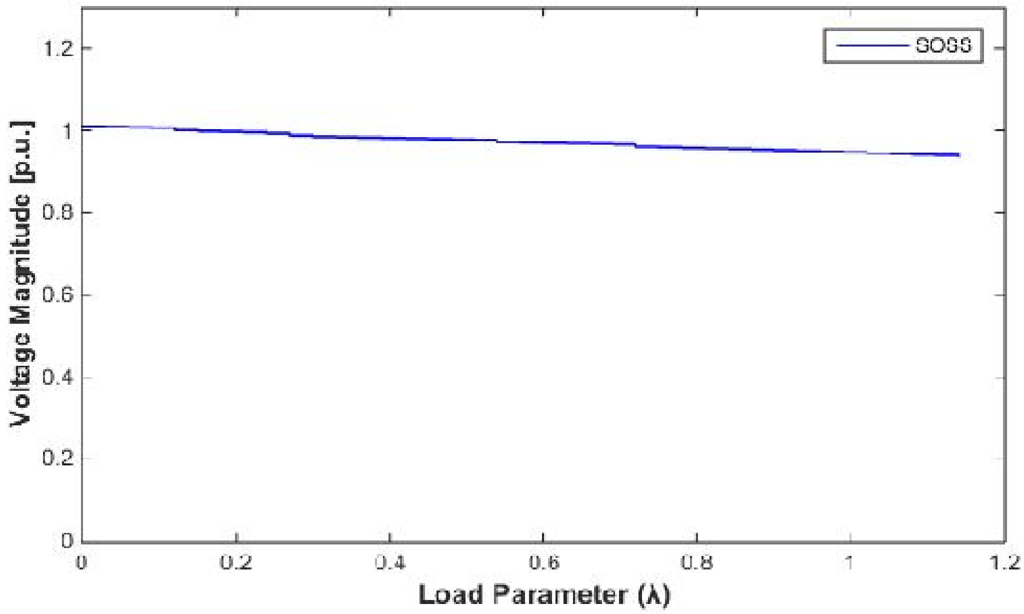

Fig. 5.29 P-V curve of the weakest bus of IEEE14- bus system with SOSS for case study 3.1

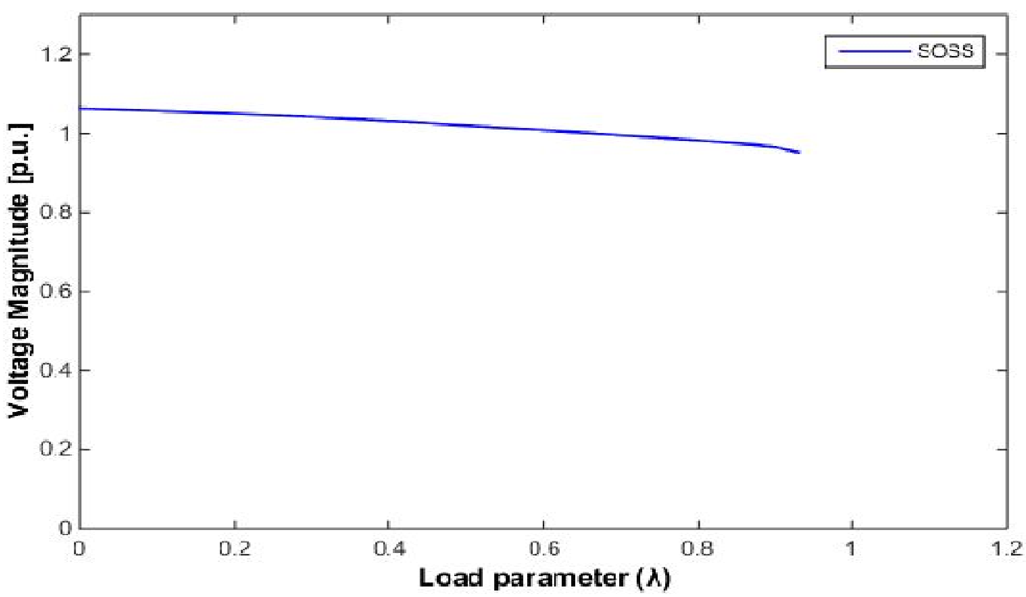

Fig .5.30 P-V curve of the weakest bus of New England 39- bus system with SOSS for case study 3.1

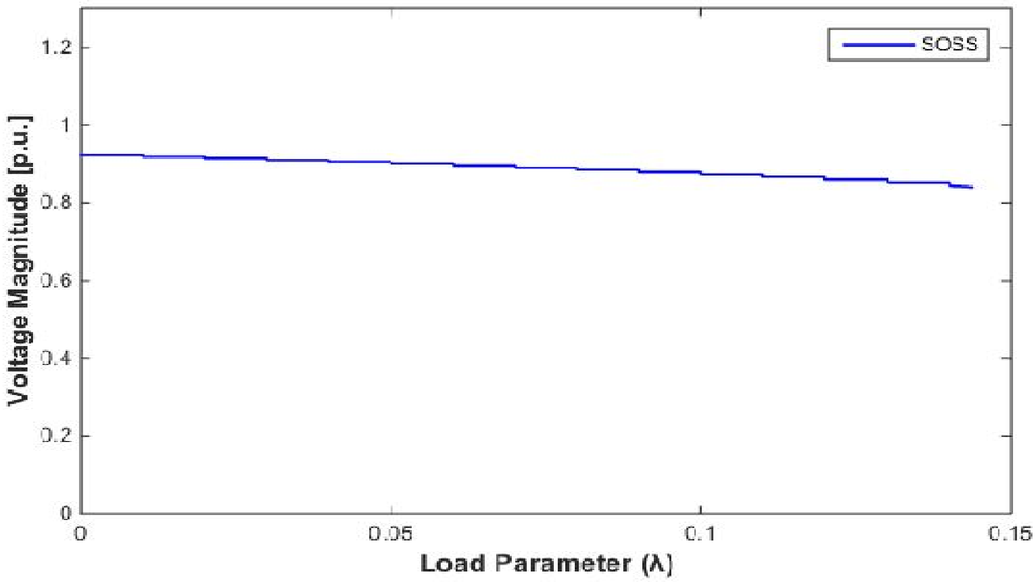

Fig. 5.31 P-V curve of the weakest bus of practical Indian 24 bus system with SOSS for case study 3.1

Figures 5.29, 5.30 and 5.31 show the p-v curves for weakest bus of the test systems considered, are for the SOS with a single objective under the optimal control variables of the UPFC parameters along with taps excluding VSL in the fitness function . The CPF for VSL resulted in values 1.14, 0.930 and 0.14356 for the test systems considered.

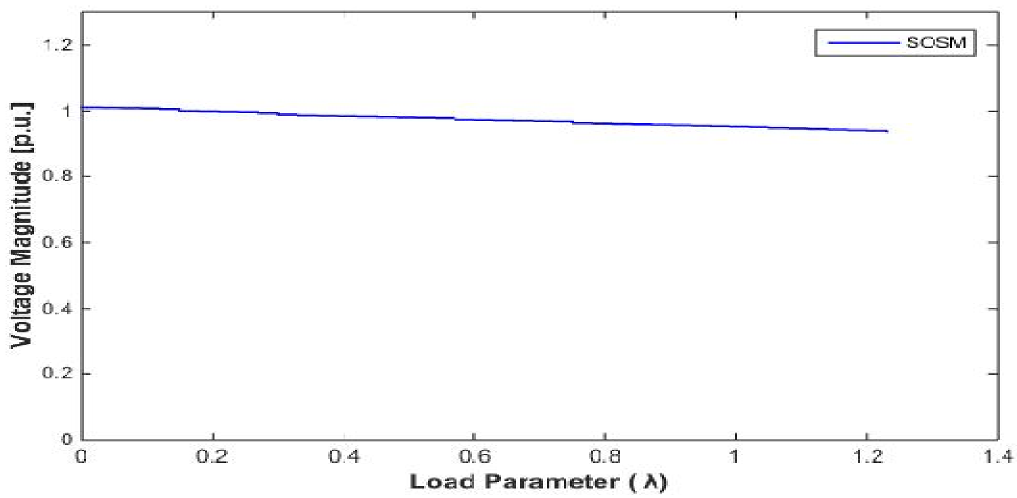

Fig. 5.32 P-V curve of the weakest bus of IEEE14- bus system with SOSM for case study 3.2

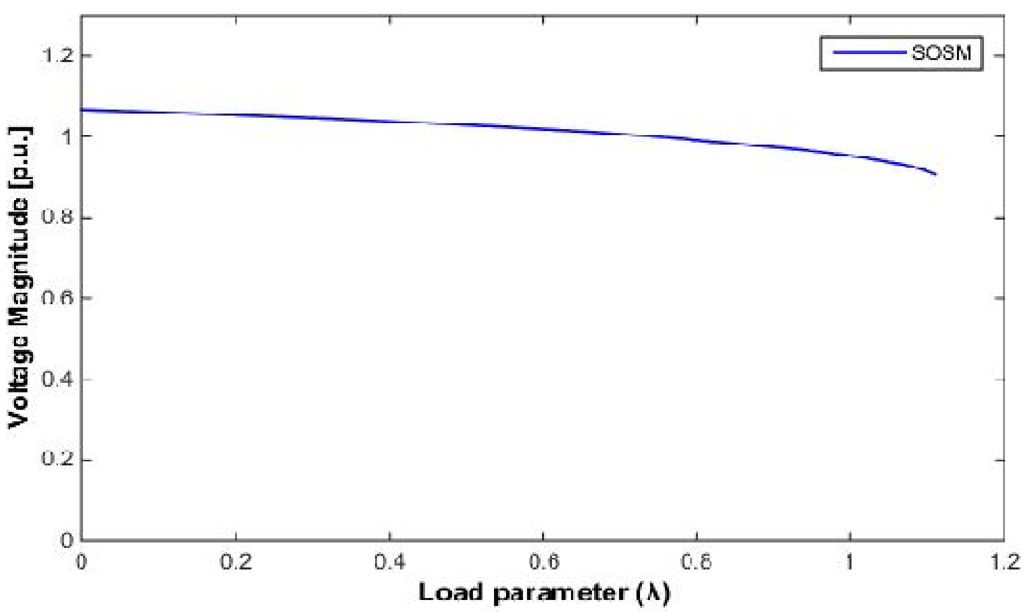

Fig. 5.33 P-V curve of the weakest bus of New England 39- bus system with SOSM for case study 3.2

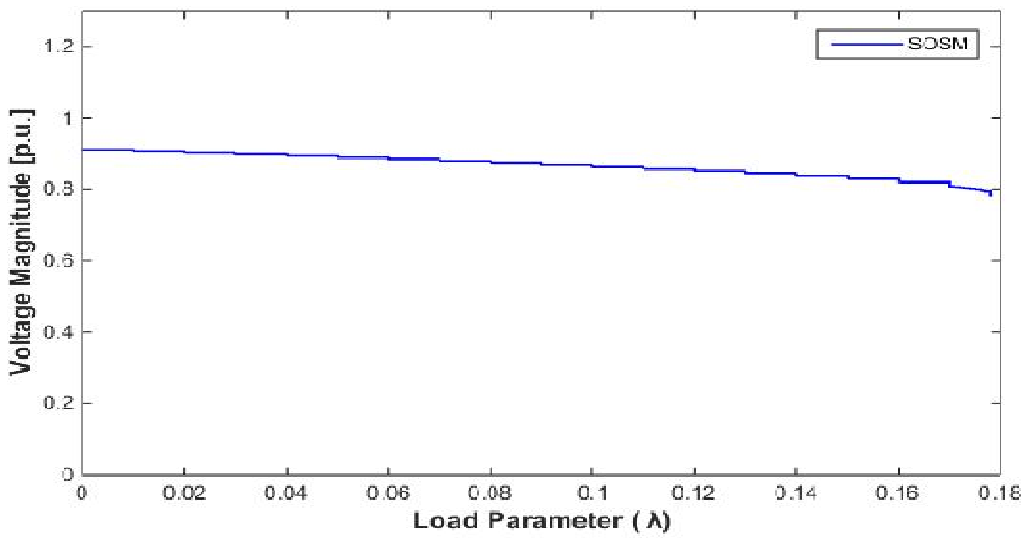

Fig. 5.34 P-V curve of the weakest bus of practical Indian 24-bus system with SOSM for case study 3.2

The figures 5.32, 5.33 and 5.34 show the p-v curves of weakest bus of IEEE 14 bus system, New England 39 bus system and Indian 24 bus system when variables are simultaneously optimized with SOS for multi-objective case. It is clear from the results that VSL has improved to 32.2580 %(from 0.93 to 1.23), 37.0370 % (from 0.81 to 1.11), and 153.2432 %(from 0.0703 to 0.17803) for IEEE 14, New England 39 and Indian 24 bus test systems respectively compared to base case. Also It is observed from the figures that the VSL has improved to 7.7947 % (form 1.14 to 1.23), 19.3548 % (from 0.93 to 1.11), and 24.0108 % (from 0.14356 to 0.17803) for IEEE 14, New England 39 and Indian 24 bus test systems respectively compared to single objective case. It can be concluded that voltage stability margin significantly improved using CPF, to ensure the feasibility of the optimal position and parameter settings of UPFC for secure operation of power system.

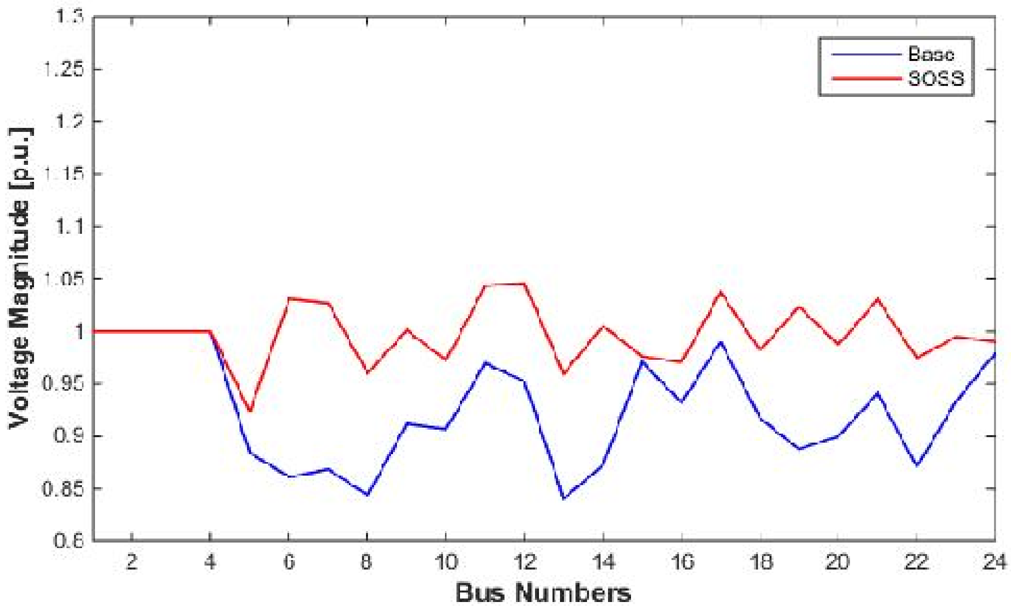

Fig. 5.35 Voltage Profiles of practical Indian 24- bus system with SOSS for case study 3.1

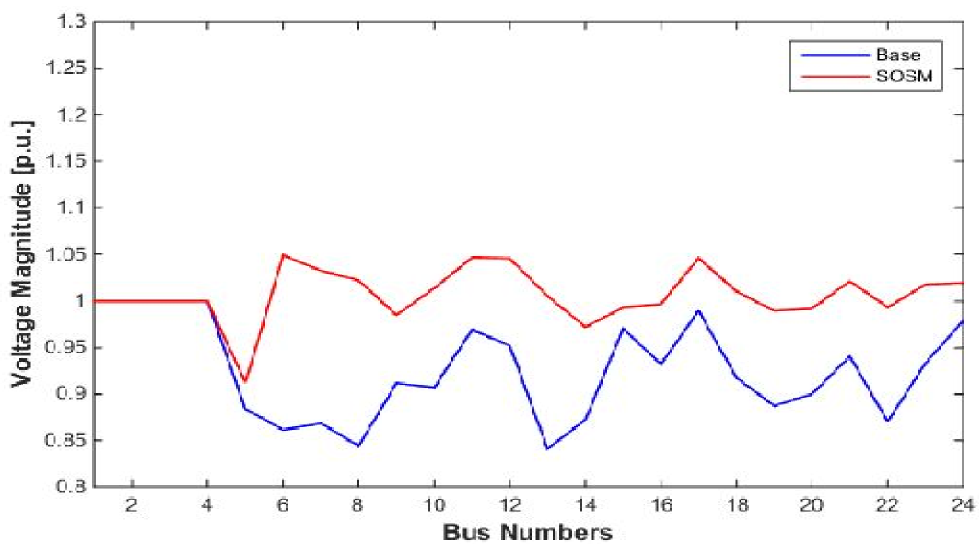

Fig. 5.36 Voltage Profiles of practical Indian 24- bus system with SOSM for case study 3.2

Figures 5.35 and 5.36 show the voltage profiles corresponding to the base case PF and with SOS of all buses of the test system considered. It is clear from the figures that SOS has helped to improve voltage profile in all the load buses which leads to significant reduction of losses and improvement in stability margin. Similar characterises can be observed for IEEE 14 bus and New England 39 bus systems

5.4.4 Case 4: Sequential optimization of OUPFC location and its parameters keeping the optimized transformer taps fixed

5.4.4.1 Case 4.1: Optimization of only RPL (single objective case)

With the optimized transformer tap values, the OUPFC location and its parameters are optimized with SOS technique for single objective of RPL minimization. The optimized OUPFC location and its parameters along with RPL and VSL obtained with proposed technique are given in tables 5.11, 5.12 and 5.13 for IEEE 14 bus, New England 39 bus and practical Indian 24-bus system respectively. The power injection model as discussed in chapter-3 is used for modelling the OUPFC. For IEEE 14-bus system only 7 lines are considered for connecting the OUPFC as the remaining 13 lines consists of transformers and feeding generator powers to the network. For New England 39 bus system 32 lines are considered for connecting the OUPFC as the remaining 14 lines consists of transformers and feeding generator powers to the network. Similarly for practical Indian 24 bus system 16 lines are considered for connecting the OUPFC as the remaining 11 lines consists of transformers and feeding generator powers to the network. It is clear that with the incorporation of OUPFC the RPL has reduced to 8.4733 % (from 0.1031to 0.094364), 1.3708 %(from 0.3500 to 0.345202), and 6.8870 %(from 0.48321 to 0.449931) for IEEE 14 bus, New England 39 bus and practical Indian 24 bus system respectively compared to case 2.1 i.e., UPFC is considered in the system. From the results it is clear that OUPFC gives better performance compared to UPFC. Also it is seen that when more nonlinear equipment like OUPFC is inducted into the system, the fitness function has successfully converged with SOS. This shows the potentiality of the proposed algorithm in solving the non liner optimization problem particularly the RPL minimization problem when OUPFC is introduced. In the single objective case VSL is not included in the fitness function. With the optimized taps the CPF is run for estimating the voltage stability limit in the single objective case and found to be 1.11, 0.96 and 0.142510 for the test systems considered.

5.4.4.2 Case 4.2: Optimization of both RPL and VSL (multi-objective case)

When both RPL and VSL are optimized in the multi-objective case, the cost function is modified. The reciprocal of VSL is added to the real power loss and the optimization is carried out with SOS technique. The optimized OUPFC parameters along with RPL and VSL obtained with proposed technique are given in tables 5.11, 5.12 and 5.13 for IEEE 14, New England 39 and Indian 24 bus test systems respectively. From the results it is seen that the VSL is improved but RPL is increased marginally with SOS technique for all the test systems. Even RPL is increased slightly; the overall multi-objective function that is the sum of real power loss and reciprocal of VSL is reduced compared to single objective case. The RPL has increased by a margin of 4.7475% (from 0.094364 to 0.098844 p.u), 2.011 % (from0.345202 to 0.352147 p.u.) and 1.5329 % (form 0.449931 p.u to 0.456828 p.u.) and VSL has improved to 5.4054 % (form 1.11 to 1.17), 4.5 % (from 0.96 to 1.08), and 18.0408% (from 0.142510 to 0.16822) for IEEE 14, New England 39 and Indian 24 bus test systems respectively compared to single objective case. But, the combined fitness function obtained with SOSM has reduced to 5.0258 %(from 9.10337 to 8.645852), 10.6925 %(from 10.76186 to 9.61114) and 14.2750 %(from 7.4674 to 6.401425) for IEEE 14 bus, New England 39 bus and practical Indian 24 bus systems respectively compared to single objective case. It is noticed that the combined fitness function reduced to 5.1977 %(from 9.11988 to 8.645852), 2.6887 % (from 9.8767 to 9.6114) and 3.1464% (from 6.609388 to 6.401425) for the test systems considered, compared to case 2.2. From the results it is clear that the percentage reduction of combined fitness function is more when OUPFC is considered compared to UPFC considered in the system. This shows the effectiveness of OUPFC for further increment of loadability limit. It is found that with SOS, the OUPFC parameters can be so optimized that the system could be loaded further beyond double its nominal loading before a voltage collapse could occur for all the test systems. So SOS is best succeeded in reducing the combined objective of loss minimization and VSL maximization with OUPFC device.

Table 5.11 Results of IEEE 14 bus system for case study 4

Control variable Settings	Optimization of RPL only (Single objective case)	Optimization of both RPL and VSL (multi-objective case)
	SOSS	SOSM
UPFC series injected voltage, $V_{se,}$ (p.u.)	0.056564	0.032438
UPFC series injected voltage angle, ρ, (deg.)	56.115081	-57.295780
PST phase angle, σ,(deg)	-9.876520	-17.449251
UPFC location	9 - 10	4-5
RPL (p.u.)	0.094364	0.098844
VSL	1.110000	1.170000
Combined fitness function (W1*RPL+W2*1/VSL)	9.10337	8.645852

Table 5.12 Results of New England 39 bus system for case study 4

Control variable Settings	Optimization of RPL only (Single objective case)	Optimization of both RPL and VSL (multi-objective case)
	SOSS	SOSM
UPFC series injected voltage, V_{se} ,(p.u.)	0.020675	0.017549
UPFC series injected voltage angle, ρ, (deg.)	-16.265388	-53.522960
PST phase angle, σ, (deg.)	-3.420569	-7.091185
UPFC location	4-14	5-8
RPL (p.u.)	0.345202	0.352147
VSL	0.960	1.08
Combined fitness function (W1*RPL+W2*1/VSL)	10.76186	9.61114

Table 5.13 Results of practical Indian 24 bus system for case study 4

Control variable Settings	Optimization of RPL only (Single objective case)	Optimization of both RPL and VSL (multi-objective case)
	SOSS	SOSM
UPFC series injected voltage, V_{se} (p.u.)	0.017097	0.016688
UPFC series injected voltage angle, ρ, (deg.)	76.238518	41.041726
PST phase angle, σ ,(deg.)	-3.881720	1.7066114
UPFC location	19-6	21-19
RPL (p.u.)	0.449931	0.456828 p.u.
VSL	0.142510	0.168220
Combined fitness function (W1*RPL+W2* 1/VSL)	7.4674	6.401424

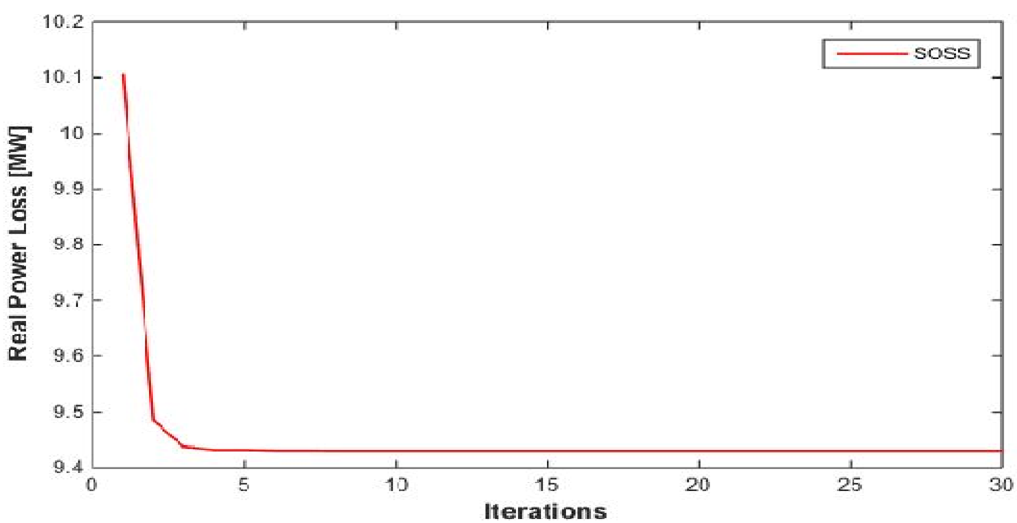

Fig.5.37 Convergence characteristic IEEE 14- bus system for case study 4.1

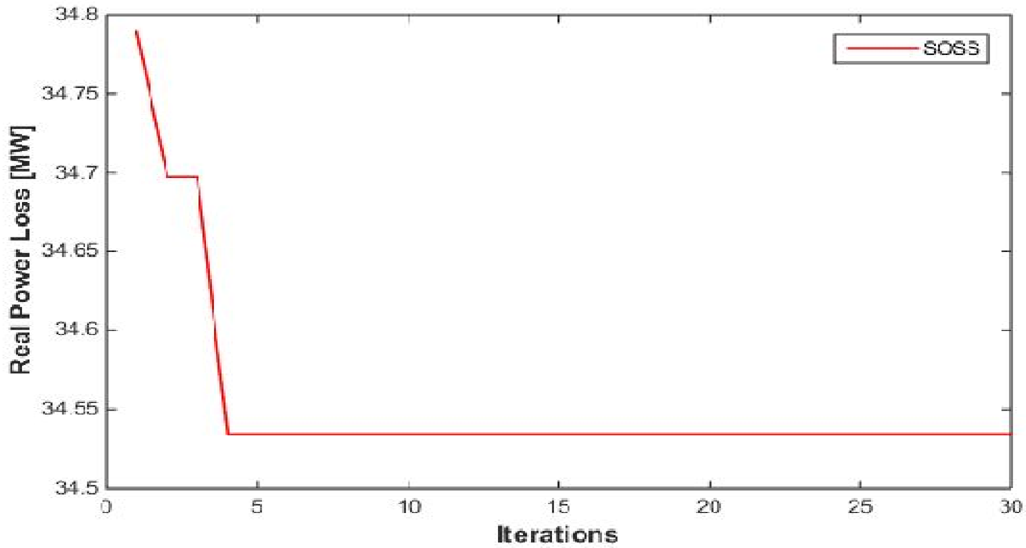

Fig. 5.38 Convergence characteristic of New England 39- bus system for case study 4.1

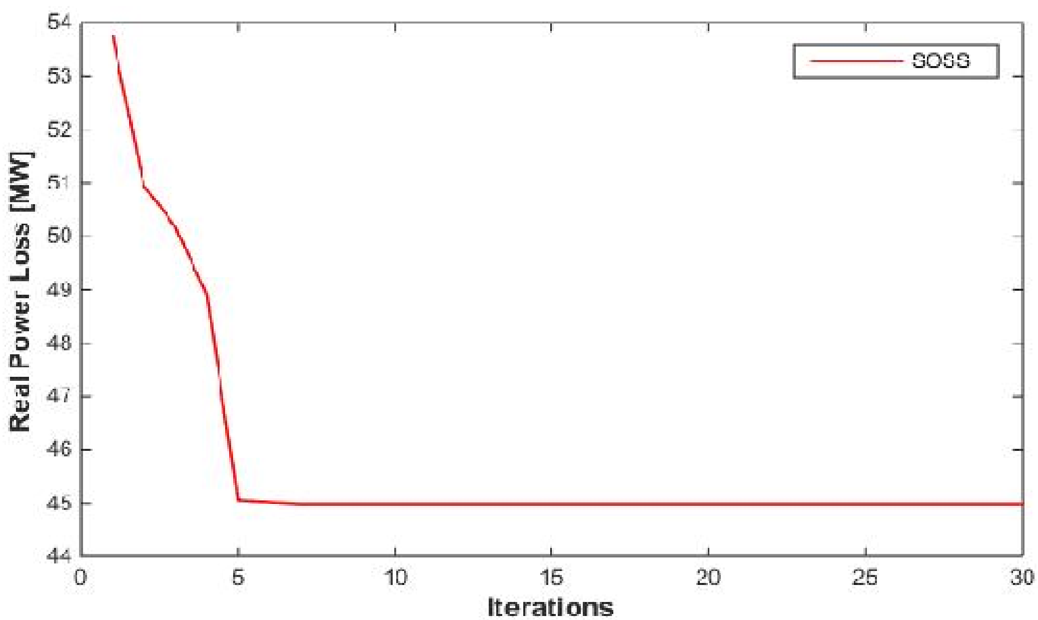

Fig. 5.39 Convergence characteristic of practical Indian 24 bus system for case study 4.1

The Figures 5.37 to 5.39 show the single objective RPL minimization, depicting the convergence. From the results it is found that the proposed SOS with OUPFC performs better in terms of loss minimization, convergence speed and accuracy. The solution started with higher value but finally reached further minimum value in the objective values and it clearly shows that global solution is reached with minimum number of iterations. Analyzing the simulation results, from the convergence point of view, it is clear that with the incorporation of OUPFC, it can be noted that the performance of SOS with OUPFC is better than the performance of SOS with UPFC (case 2.1).

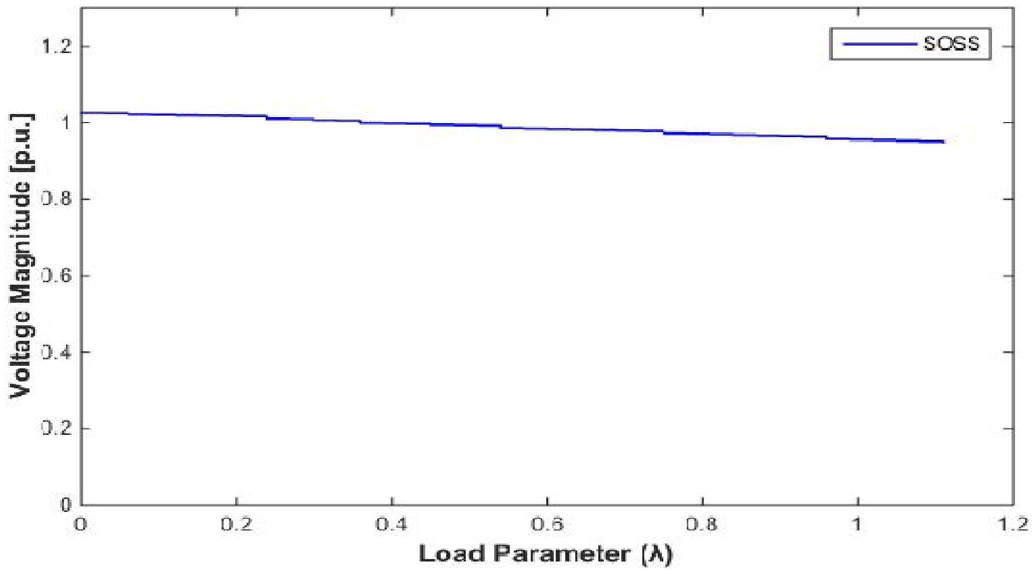

Fig. 5.40 P-V curve of weakest bus of IEEE 14- bus system with SOSS for case study 4.1

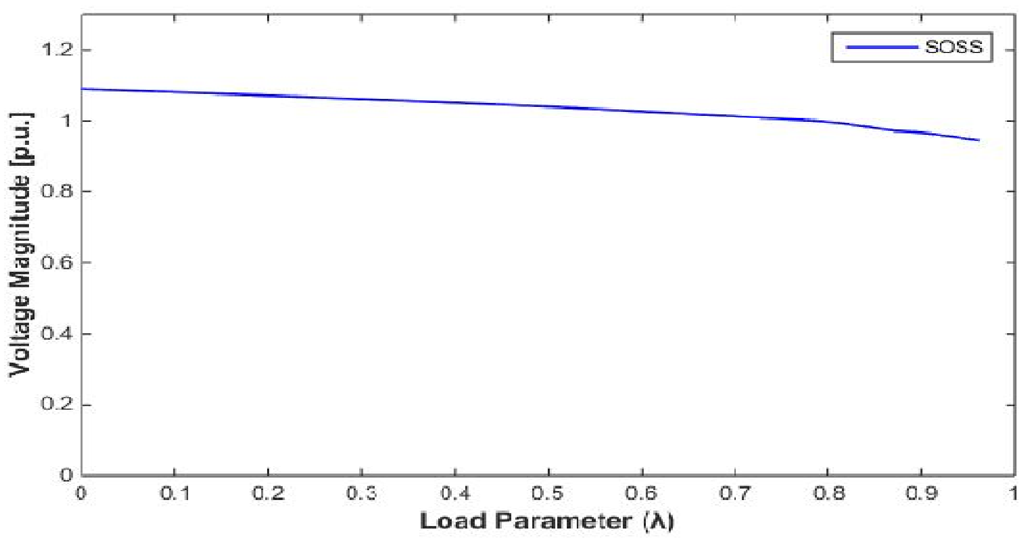

Fig. 5.41 P-V curve of the weakest bus of New England 39- bus system with SOSS for case study 4.1

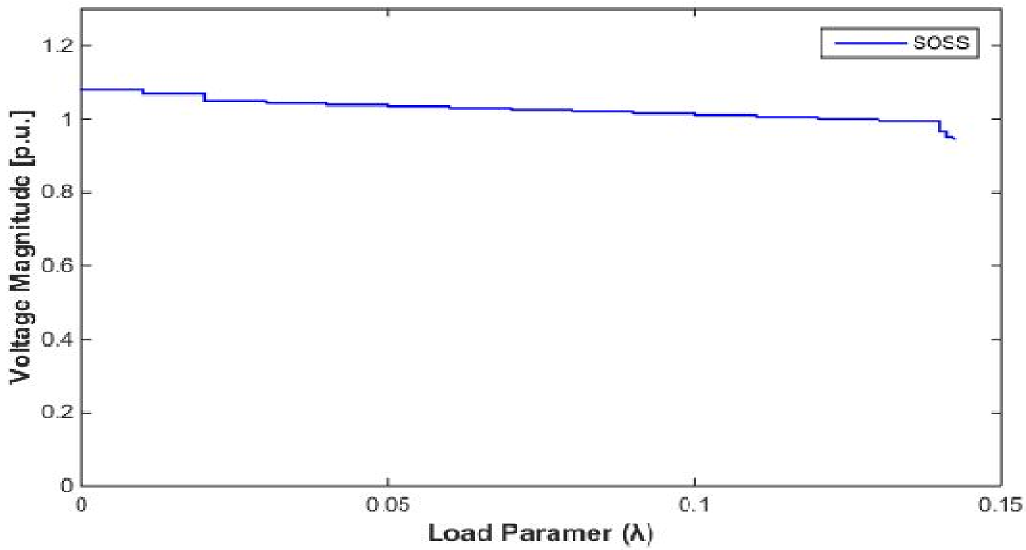

Fig. 5.42 P-V curve of the weakest bus of practical Indian 24 bus system with SOSS for case study 4.1

Figures 5.40, 5.41 and 5.42 show the p-v curves for weakest bus of the test systems considered, are for the SOS with a single objective under the optimal control variables of the OUPFC location and its parameters excluding VSL in the fitness function . The CPF for VSL resulted in values 0.96, 0.93 and 0.147330 for the test systems considered.

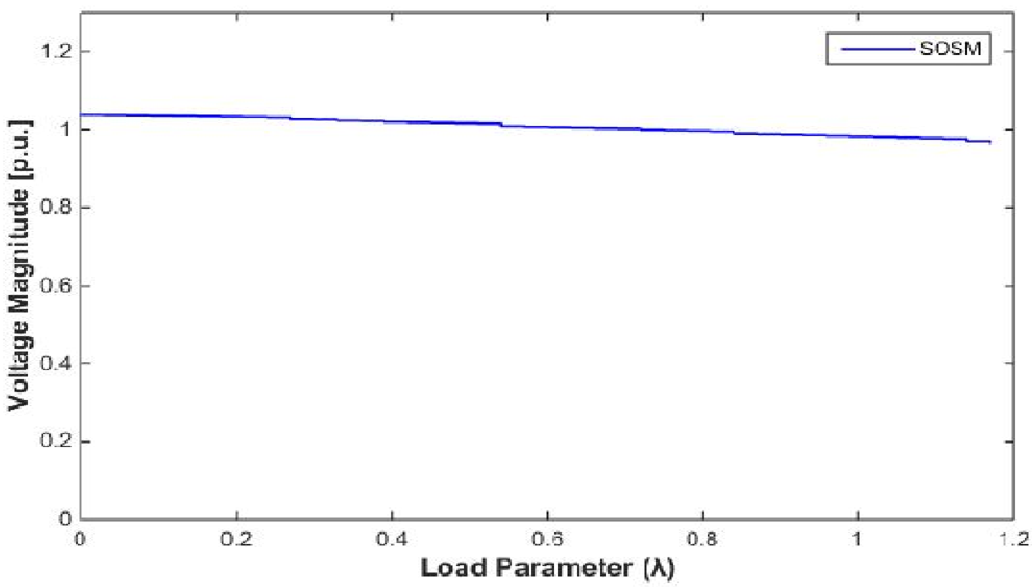

Fig. 5.43 P-V curve of weakest bus of IEEE 14- bus system with SOSM for case study 4.2

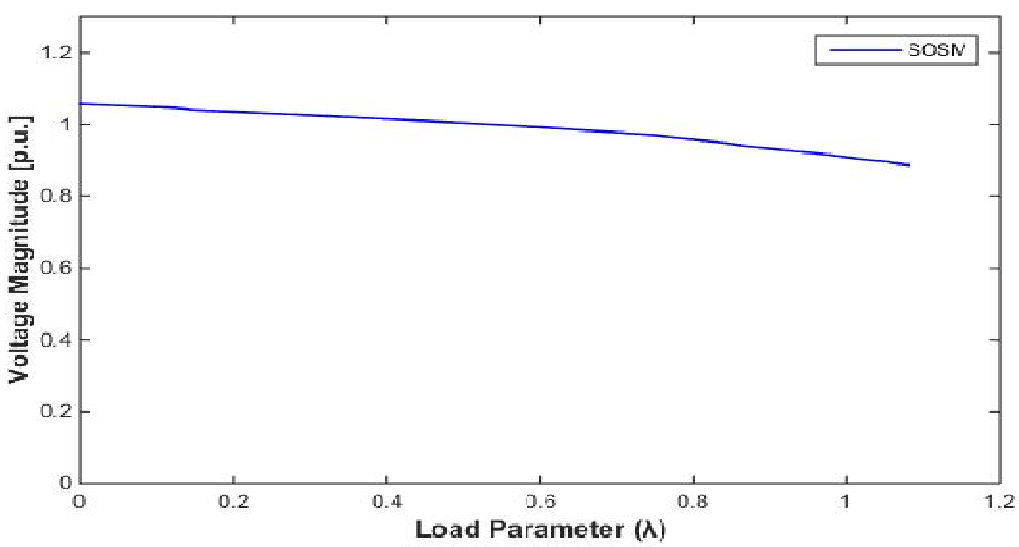

Fig. 5.44 P-V curve of the weakest bus of New England 39- bus system with SOSM for case study 4.2

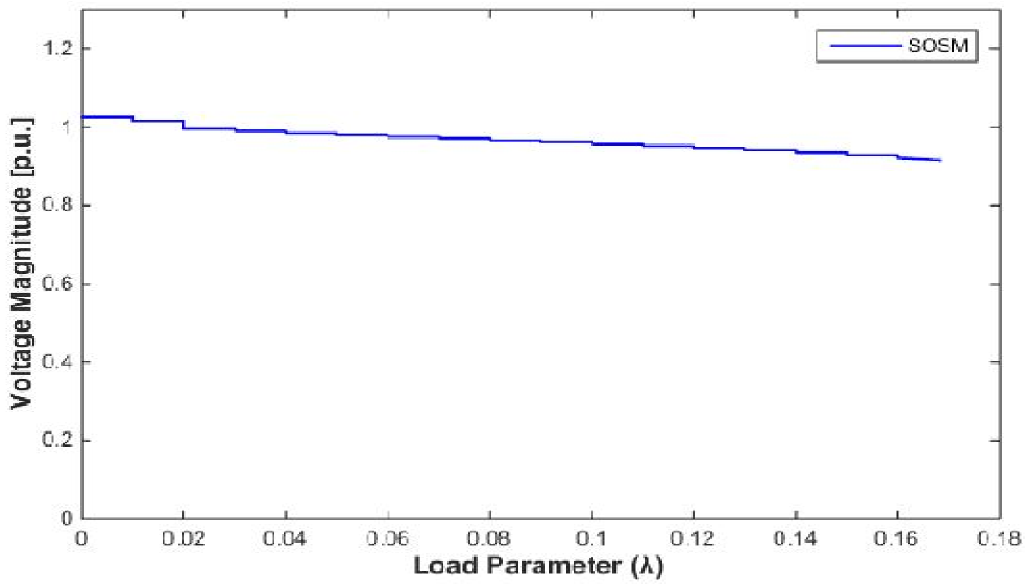

Fig. 5.45 P-V curve of the weakest bus of practical Indian 24-bus system with SOSM for case study 4.2

Figures 5.43, 5.44 and 5.45 show the p-v curves of weakest bus of IEEE 14 bus system, New England 39 bus system and Indian 24 bus system when OUPFC variables are sequentially optimized with SOS for multi-objective case. It is clear from the results that VSL has improved to 25.8064 %(from 0.93 to 1.17), 33.333 % (from 0.81 to 1.08), and 139.288 %(from 0.0703 to 0.168220) for IEEE 14, New England 39 and Indian 24 bus test systems respectively compared to base case . Also It is observed from the figures that the VSL has improved to VSL has improved to 5.4054 % (form 1.110 to 1.17), 2.8571 % (from 1.05 to 1.08), and 2.6357% (from 0.1639 to 0.16822) for IEEE 14, New England 39 and Indian 24 bus test systems respectively compared to case 2.2. Also It is observed from the figures that the VSL has improved to VSL has improved to 5.4054 % (form 1.11 to 1.17), 4.5 % (from 0.96 to 1.08), and 18.0408% (from 0.142510 to 0.16822) for IEEE 14, New England 39 and Indian 24 bus test systems respectively compared to single objective case. It can be concluded that voltage stability margin was further more improved using CPF, to ensure the feasibility of the optimal position and parameter settings of OUPFC for secure operation of power system

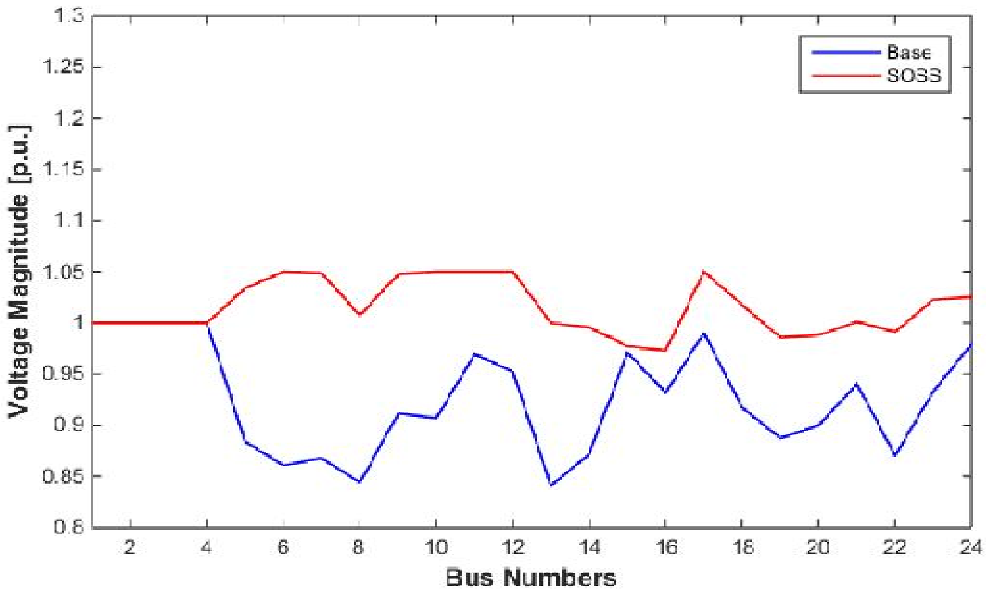

Fig. 5.46 Voltage Profiles of practical Indian 24- bus system with SOSS for case study 4.1

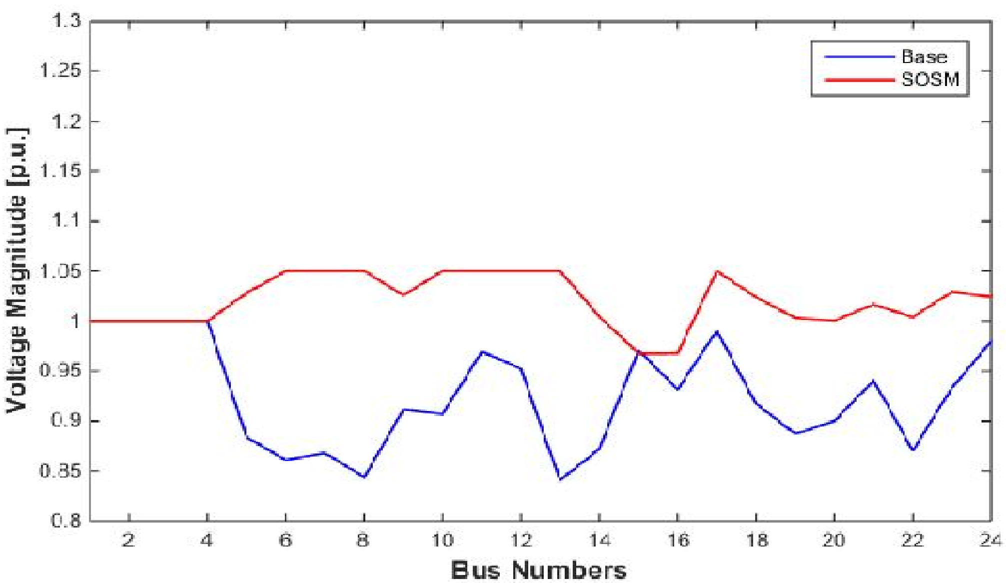

Fig. 5.47 Voltage Profiles of practical Indian 24- bus system with SOSM for case study 4.2

Figures 5.46 and 5.47 show the voltage profiles corresponding to the base case PF and with SOS of all buses of the test system considered. It is clear from the figures that SOS has helped to improve voltage profile in all the load buses which leads to further reduction of losses and improvement in stability margin. Similar characterises can be observed for the test systems considered.

5.4.5 Case 5: Simultaneous optimization of OUPFC location and its parameters along with taps

5.4.5.1 Case 5.1: Optimization of only RPL (single objective case)

Simultaneous optimization of OUPFC location and its variables along with the transformer taps with SOSS could still reduce the objective function. For optimizing with the SOSS, the number of variables now becomes 6 i.e., 3 transformer tap positions, and 3 UPFC variables, 15, i.e., 12 transformer tap positions, and three UPFC variables 14, i.e,11 transformer tap positions, and 3 UPFC variables for IEEE 14- bus, New England 39- bus and practical Indian 24 -bus system respectively. The optimized transformer taps, OUPFC location and its parameters along with RPL and VSL obtained with proposed technique are given in tables 5.14, 5.15 and 5.16 for the test systems considered. Also the RPL is reduced to 7.6329 % (from 0.09852 to 0.091), 2.7876 %(from 0.33 to 0.3208006) and 3.9586 % (from 0.45 to 0.432186) for IEEE 14 bus, New England 39 bus and practical Indian 24 bus system respectively compared to case 3.1.With the optimized taps the CPF is run for estimating the voltage stability limit in the single objective case and found to be 1.14, 0.930 and 0.191126 for IEEE 14 bus, New England 39 bus and practical Indian 24 bus system respectively.

5.4.5.2 Case 5.2 Optimization of both RPL and VSL (multi-objective case)

When both RPL and VSL are optimized in the multi-objective case, the cost function is modified. The reciprocal of VSL is added to the real power loss and the optimization is carried out with SOSM technique. The optimized transformer taps, UPFC parameters along with RPL and VSL obtained with proposed technique are given in tables 5.14, 5.15 and 5.16 for IEEE 14, New England 39 bus and practical Indian 24 bus test systems respectively. From the results it is seen that the VSL is improved but RPL is increased marginally with SOSM technique for all the test systems. Even RPL is increased slightly; the overall multi-objective function that is the sum of real power loss and reciprocal of VSL is reduced compared to single objective case. Here RPL has increased by a margin of 4.6439 % (from 0.091 to 0.095226), 8.0057 % (from 0.3208006 to 0.346483) and 2.7402 % (form 0.432186 to 0.444029) and VSL has improved to 7.8947 % (form 1.14 to 1.23), 22.5806 % (from 0.93 to 1.14), and 12.3499 % (from 0.191126 to 0.214730) for IEEE 14, New England 39 and practical Indian 24 bus test systems respectively compared to single objective case. But, the combined fitness function obtained with SOSM has reduced to 7.1940 %(from 8.8629 to 8.22530), 17.7089 %(from 11.08069 to 9.118412) and 9.9535 %(from 5.6649 to 5.10104) for IEEE 14 bus, New England 39 bus and practical Indian 24 bus systems respectively compared to single objective case. It is noticed from the results that the combined fitness function reduced to 0.051% (from 8.22953 to 8.225307),3.4158 (from 9.4409 to 9.118412), and 15.9593% (6.06973 to 5.10104) for IEEE 14 bus, New England 39 bus and practical Indian 24 bus systems respectively compared to case 3.2. It is found that with SOSM, when OUPFC variables are simultaneously optimized that the system could be more loaded before a voltage collapse could occur for all the test systems compared to case 3.2. So SOS is best succeeded in reducing the combined objective of loss minimization and VSL maximization considering with OUPFC.

Table 5.14: Results of IEEE 14 bus system for case study 5

Control variable Settings	Optimization of RPL only (Single objective case)	Optimization of both RPL and VSL (multi-objective case)
	SOSS	SOSM
T_1 (4-7)	0.95	1.00
T_2 (4-9)	0.90	1.05
T_3 (5-6)	1.05	1.10
UPFC series injected voltage, V_{se} ,(p.u.)	0.077415	0.015288
UPFC series injected voltage angle, ρ, (deg.)	55.379828	57.295780
PST phase angle ,σ.(deg.)	-5.753732	14.732209
UPFC location	9-10	4-5
RPL (p.u.)	0.091000	0.095226
VSL	1.14	1.23
Combined fitness function (W1*RPL+W2* 1/VSL)	8.8629	8.225307

Table 5.15 Results of New England 39 bus system for case study 5

Control variable Settings	Optimization of RPL only (Single objective case)	Optimization of both RPL and VSL (multi-objective case)
	SOSS	SOSM
T_1 (2-30)	1.00	1.00
T_2 (10-32)	1.00	1.00
T_3 (12-11)	1.00	1.05
T_4 (12-13)	1.05	1.10
T_5 (19-33)	1.00	1.10
T_6(19-20)	1.05	0.95
T_7 (20-34)	0.95	1.05
T_8 (22-35)	1.00	1.05
T_9(23-36)	1.05	1.10
T_{10}(25-37)	1.05	1.05
T_{11} (29-38)	1.05	1.00
T_{12} (31-6)	1.00	1.15
UPFC series injected voltage, V_{se} ,(p.u.)	0.011660 p.u	0.00600
UPFC series injected voltage angle, ρ, (deg.)	0.010254	-9.816256
PST phase angle, σ , (deg.)	-0.002117	13.063453
UPFC location	5-8	5-8
RPL (p.u.)	0.328006	0.346483
VSL	0.9300	1.1400
Combined fitness function (W1*RPL+W2*1/VSL)	11.08069	9.118412

Table 5.16 Results of practical Indian 24- bus test system for case study 5

Control variable Settings	Optimization of RPL only (Single objective case)	Optimization of both RPL and VSL (multi-objective case)
	SOSS	SOSM
T_1(15-1)	1.0000	0.9875
T_2 (17-2)	1.0250	1.0125
T_3 (24-3)	1.0125	1.0000
T_4 (21-4)	1.0375	1.0125
T_5 (16-5)	0.9375	0.9875
T_6 (19-6)	0.9250	0.9500
T_7 (20-7)	0.9125	0.9625
T_8 (14-8)	0.9250	0.9375
T_9 (23-9)	0.9750	0.9500
T_{10} (18-10)	0.9875	1.0000
T_{11} (22-13)	0.9250	1.0000
UPFC series injected voltage, V_{se} ,(p.u.)	0.040379	0.036823
UPFC series injected voltage angle, ρ, (deg.)	89.380233	65.422391
PST phase angle, σ , (deg.)	-13.279064	-1.604335
UPFC location	14-8	14-8
RPL (p.u.)	0.432186	0.444029
VSL	0.191126	0.214730
Combined fitness function (W1*RPL+W2*1/VSL)	5.6649	5.101040

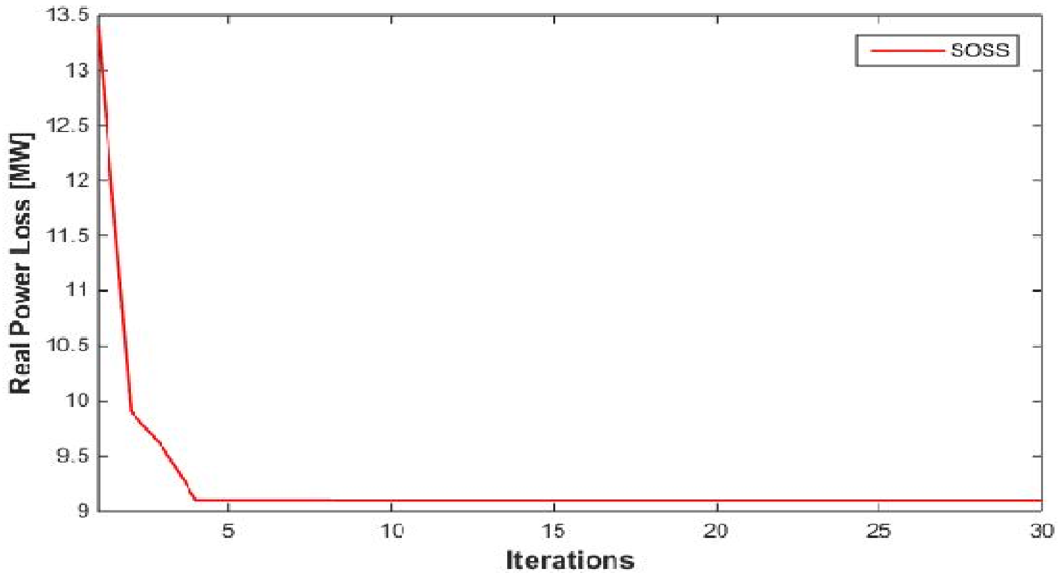

Fig. 5.48 Convergence characteristic of IEEE 14- bus system for case study 5.1

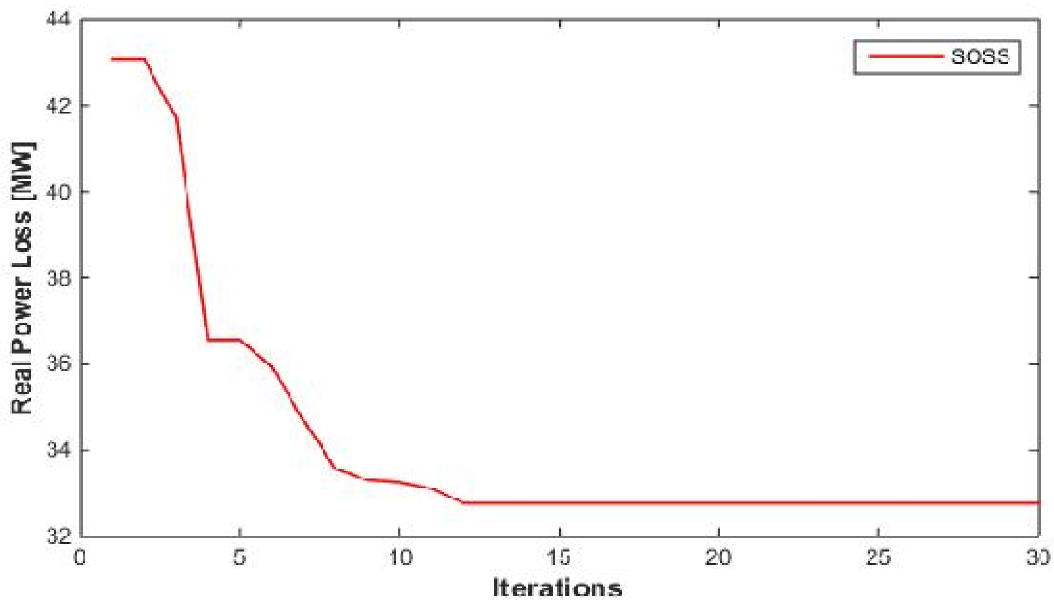

Fig. 5.49 Convergence characteristic of New England 39- bus system for case

study 5.1

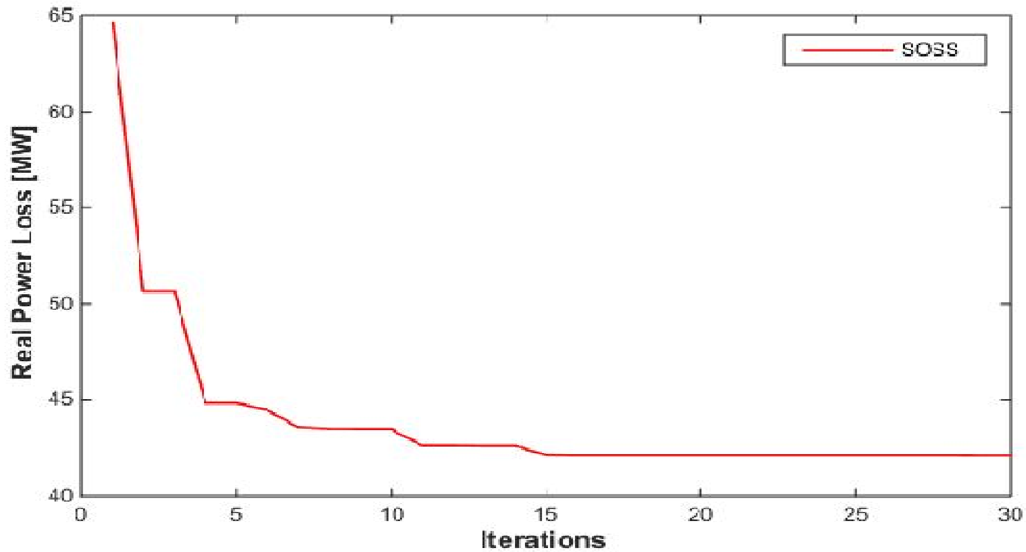

Fig. 5.50 Convergence characteristic of practical Indian 24-bus system for case study 5.1

The Figures 5.48 to 5.50 show the single objective RPL minimization, depicting the convergence. From the results it is found that the proposed algorithm performs better in terms of loss minimization, convergence speed and accuracy. The solution started with higher value but finally reached further minimum value in the objective values and it clearly shows that global solution is reached with minimum number of iterations. Analyzing the simulation results, from the convergence point of view, it is clear that when variables are simultaneously optimized, it can be noted that the performance of SOS is better than the performance of case 3.1.

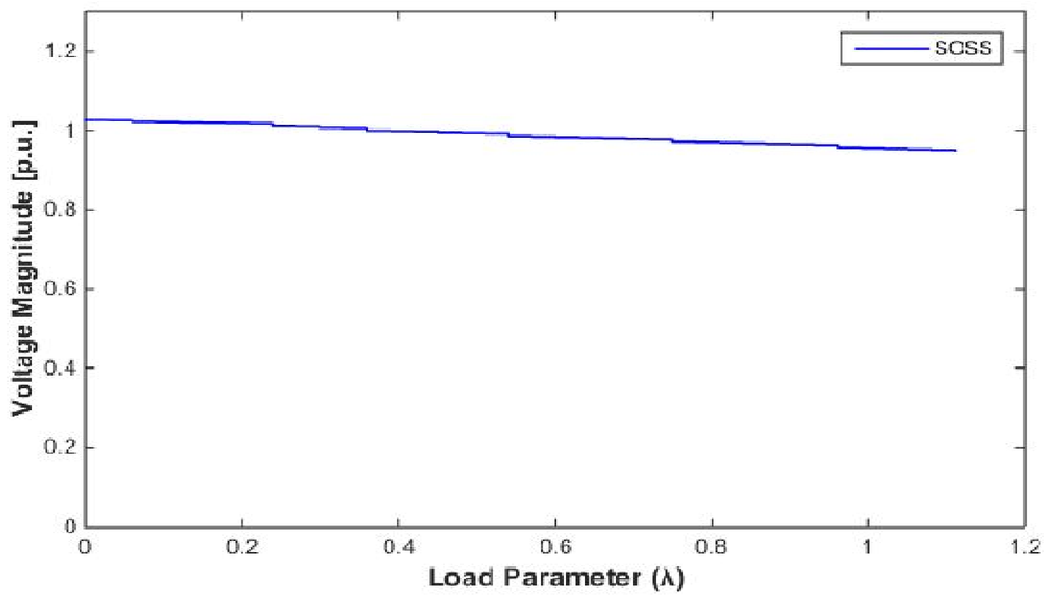

Fig. 5.51 P-V curve of weakest bus of IEEE 14- bus system with SOSS for case study 5.1

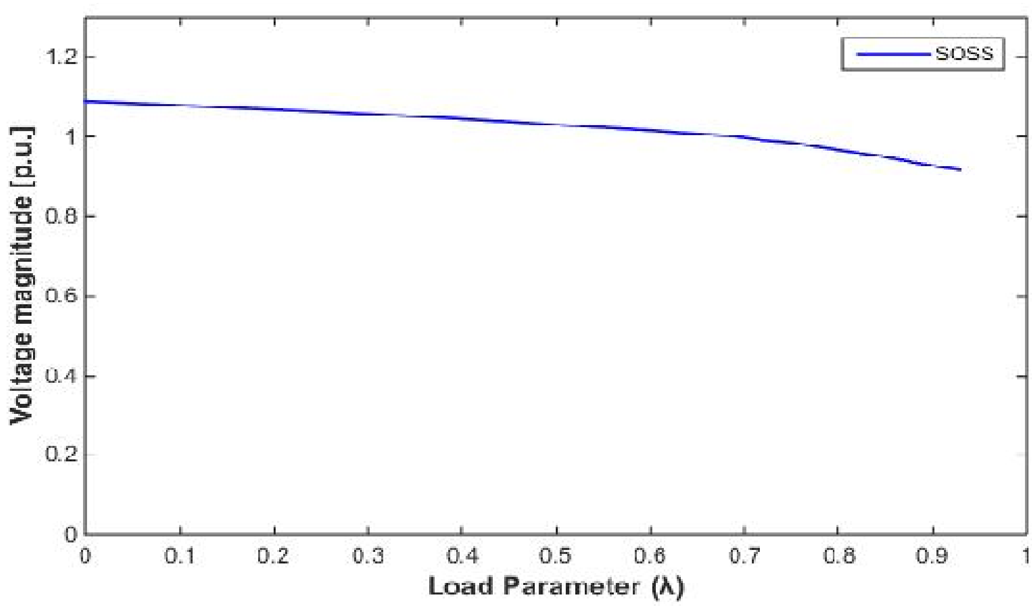

Fig. 5.52 P-V Curve of weakest bus of New England 39-bus system with SOSS for case study 5.1

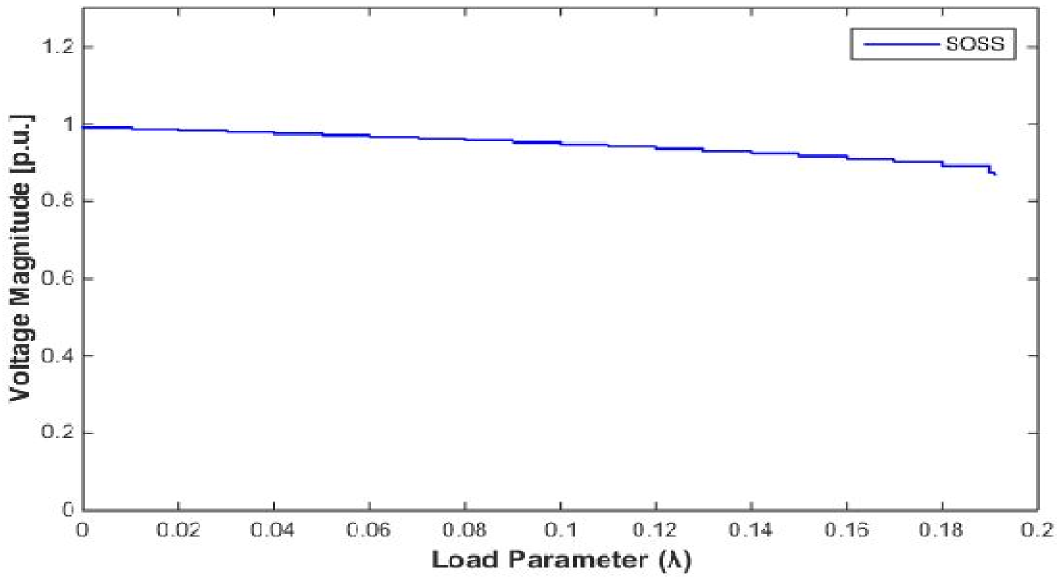

Fig. 5.53 P-V Curve of weakest bus of practical Indian 24-bus system with SOSS for case study 5.1

The figures 5.51, 5.52 and 5.53 show the p-v curves for weakest bus of the test systems considered, are for the SOS with a single objective under the optimal control variables of the OUPFC parameters along with taps excluding VSL in the fitness function . The CPF for VSL resulted in values 1.14, 0.93 and 0.191126 for the test systems considered.

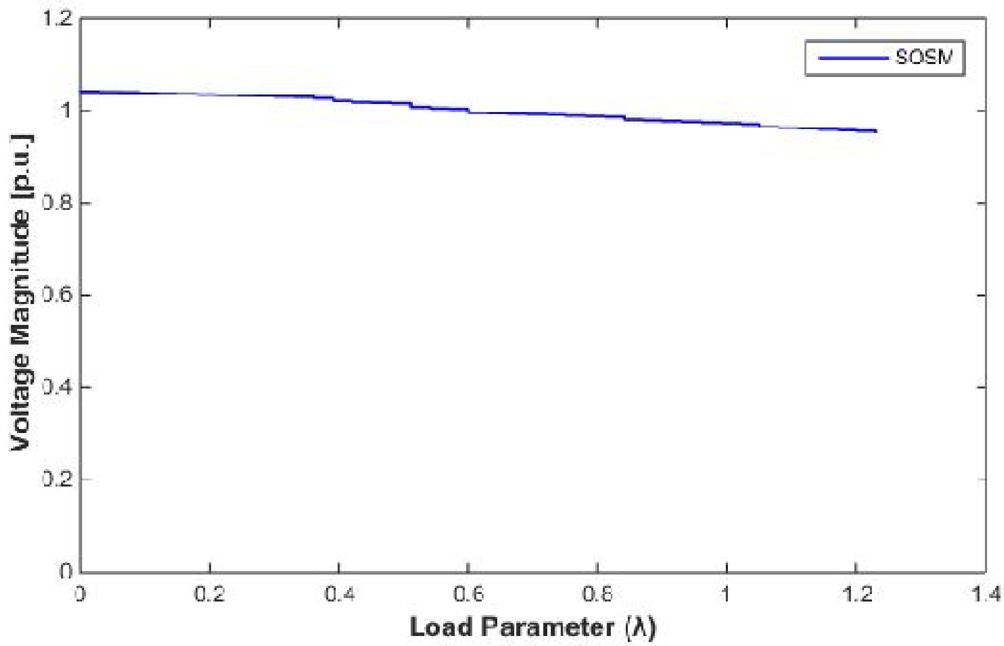

Fig. 5.54 P-V curve of weakest bus of IEEE 14 bus system with SOSM for case study 5.2

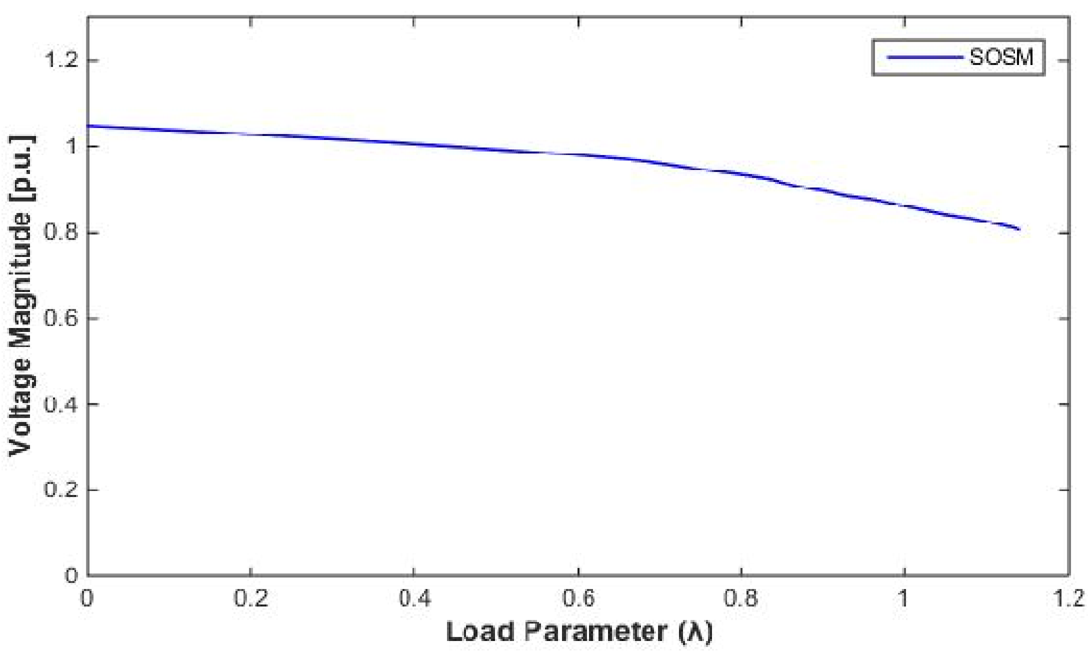

Fig. 5.55 P-V Curve of weakest bus of New England 39- bus system with SOSM for case study 5.2

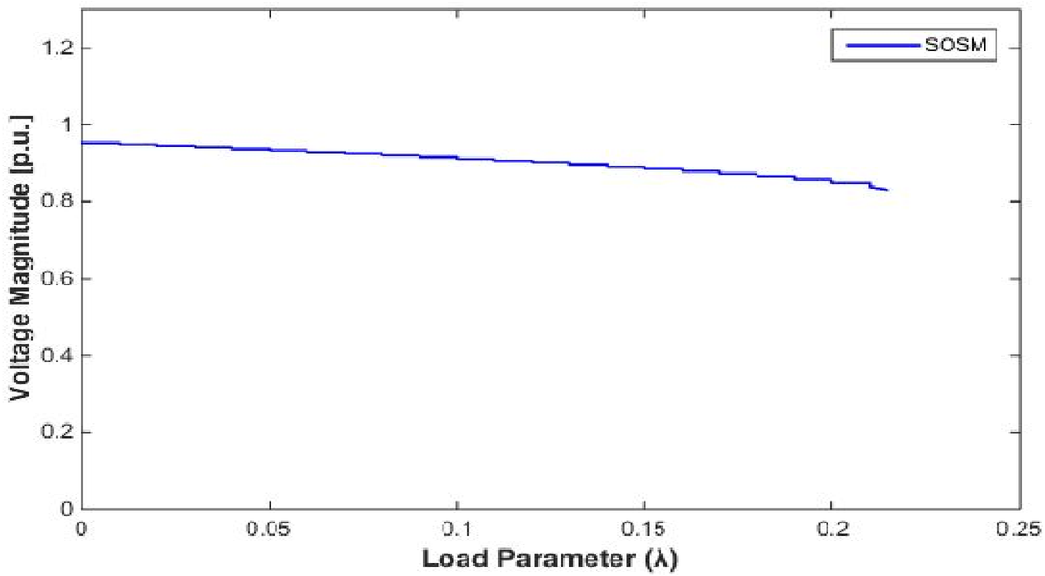

Fig. 5.56 P-V Curve of weakest bus of practical Indian 24- bus system with SOSM for case study 5.2

Figures 5.54, 5.55 and 5.56 show the p-v curves of weakest bus of IEEE 14 bus system, New England 39 bus system and Indian 24 bus system when OUPFC variables along with taps are simultaneously optimized obtained with SOS for multi-objective case. It is clear from the results that VSL has improved to 32.2580 %(from 0.93 to 1.23), 40.7407 % (from 0.81 to 1.14), and 205.4480 %(from 0.0703 to 0.214730) for IEEE 14, New England 39 and Indian 24 bus test systems respectively compared to base case . Also It is observed from the figures that the VSL has improved to VSL has improved to 0 % (form 1.23 to 1.23), 2.7027 % (from 1.11 to 1.14), and 20.6145 % (from 0.17803 to 0.214730) for IEEE 14, New England 39 and Indian 24 bus test systems respectively compared to case 3.2. Also It is observed from the figures that the VSL has improved to VSL has improved to 7.8947 % (form 1.14 to 1.23), 22.5806 % (from 0.93 to 1.14), and 12.3499 % (from 0.191126 to 0.214730) for IEEE 14, New England 39 and Indian 24 bus test systems respectively compared to single objective case. It can be concluded that voltage stability margin significantly improved using CPF, to ensure the feasibility of the optimal position and parameter settings of OUPFC for secure operation of power system.

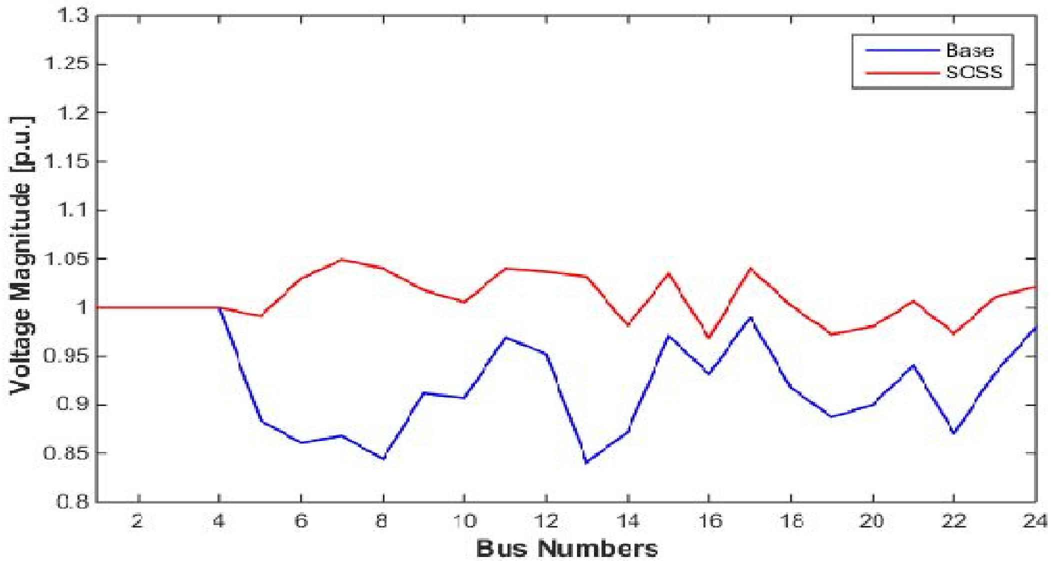

Fig. 5.57 Voltage Profiles of practical Indian 24- bus system with SOSS for case study 5.1

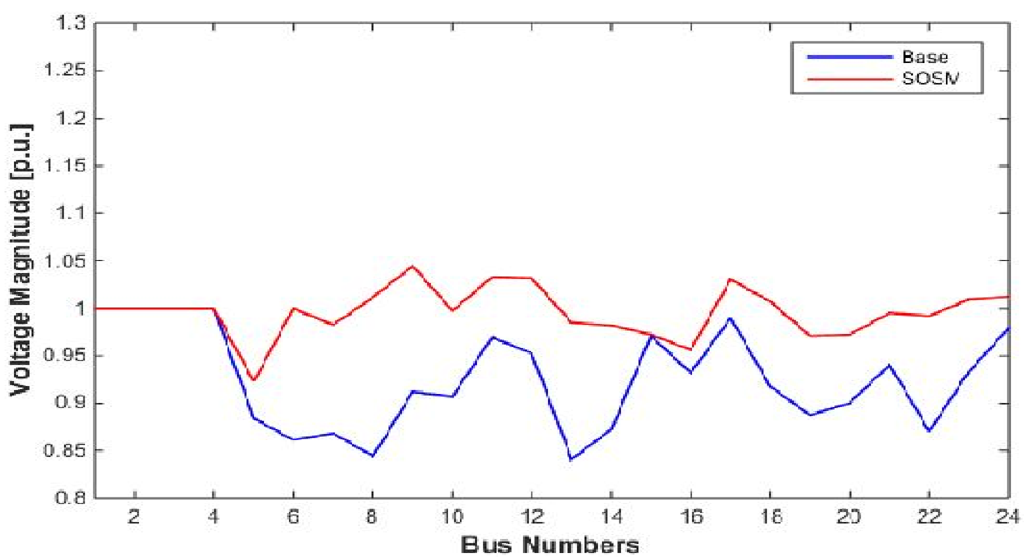

Fig.5.58 Voltage Profiles of practical Indian 24- bus system with SOSM for case study 5.2

The Figures 5.57 and 5.58 show the voltage profiles corresponding to the base case PF and with SOS of all buses of the test system considered. It is clear from the figures that SOS has helped to improve voltage profile in all the load buses which leads to significant reduction of losses and improvement in stability margin. Similar characterises can be observed for test systems considered.

5.5. PARAMETERS TUNING OF SOS ALGORITHM

Determination of the parameters such as ecosystem size, benefit factors (BF1 and BF2) are important to implement SOS successfully, because they affect the performance of the algorithm for various problems. Under a fixed iteration number of 30, the parameter settings for the algorithm are varied with several trials as shown in table 5.17 for IEEE 14-bus system and the optimal settings for best result are chosen. From the tables, the trial 6 gives the best values for RPL over the other trials. Based on the trials the population size of 40 is chosen and the values of BF1 and BF2 are set as 1, and 2 respectively. For New England 39-bus and practical Indian 24- bus systems also the same parameters are applied.

Table 5.17: Influence of control parameters on the performance on SOS for IEEE 14-bus test system

Trial	Ecosystem size	BF1	BF2	RPL (p.u)		
				Case 1.1	Case 2.1	Case 3.1
1	30	1	2	0.13371	0.10423	0.098991
2	30	1	3	0.13424	0.10431	0.099134
3	40	1	2	0.13307	0.10317	0.098523
4	40	1	3	0.13321	0.10371	0.098991
5	50	1	2	0.13307	0.10317	0.098523

5.6. ROBUSTNESS OF THE SOS ALGORITHM

To test the robustness of SOS algorithm, 10 trial runs were performed for the IEEE 14- bus system and for New England 39-bus test system. Tables 5.18 and 5.19 show the results of RPL values and computational time for case studies 1.1, 2.2 and 3.1 of IEEE-14 bus test system and New England 39- bus system. It can be seen here that the optimal RPL obtained by the proposed SOS for all the three cases are always nearer to the average value, showing the robustness and superiority of the proposed SOS method for the OPF problem of RPL minimization. Same observations are made for the practical Indian 24 bus system.

Table 5.18: RPL values and computational time for IEEE 14-bus system for 10 trials

S. No	Case study	RPL (p.u.)			Simulation time(s)
		Best value	worst value	Average value	
1	1.1	0.133077	0.134079	0.13353	54.04
2	2.1	0.103175	0.11065	0.10739	56.5
3	3.1	0.098523	0.101335	0.099181	59.2

Table 5.19: RPL values and computational time for of New England 39-bus system for 10 trials

S. No	Case study	RPL (p.u.)			Simulation time(s)
		Best value	worst value	Average value	
1	1.1	0.4011p.u.	0.4203p.u.	0.4067 p.u.	123.4
2	2.1	0.3500 p.u.	0.3619p.u.	0.3518p.u.	137.2
3	3.1	0.3300 p.u	0.3428p.u.	0.3321p.u.	133.7

From tables 5.18 and 5.19, it is also clear that the proposed SOS method is computationally efficient and the time requirement is vey less.

5.7 CONCLUSION

SOS method has been successfully implemented to find the optimum control variables for the problem of RPL minimization (single objective case) and for simultaneous optimization of RPL and VSL (multi-objective case). Transformers tap settings, UPFC and OUPFC parameters are considered as control variables. The UPFC and OUPFC devices are considered separately during the optimization process. The effectiveness of the proposed method is demonstrated on the test systems considered. In multi-objective case even though there is slight increase in the real power loss, the VSL has improved and the combined fitness function has reached optimal solution with the proposed algorithm. From the simulation results it can be concluded that the proposed algorithm is capable of finding optimum control variables for both single and multi-objective optimization problems and so helpful for stable and secure operation of the power system. The results also indicate the better convergence characteristics, computational efficiency and robustness of the proposed SOS algorithm.