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Optimal DSSC's deployment in power system using PSO

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ABSTRACT

Owing to the high cost of installation and operation, distributed flexible AC transmission system (FACTS) technology gives opportunity to provide cost-effective solution in power system operation and control. A distributed static series compensator (DSSC) is a series FACTS device and it is placed equidistantly placed on the existing line to vary the line current. Active power can be controlled in the line with the help of DSSC. This paper presents DSSC for active power flow control to enhance system loadability index and to minimize reactive power generation by generators. Since DSSC is of low power. a small value of reactance is emulated in the line. Large number of DSSC's are distributed along the transmission line at regular intervals to realize considerable change in the current. A particle swarm optimization is implemented to determine DSSC's emulated reactance optimally. In this condition, all the lines flowing power in their limits with increased loading condition. Maximum system loadability index is evaluated by employing optimal number of DSSC's on the line. A multiobjective problem is formulated. One objective function is formed such that no line would become overloaded even when loading is increased. Other objective is formulated to minimize reactive power generation by generators. A compromise solution is investigated for optimally connected of DSSC devices to achieve both the objective functions. IEEE 14 bus system is taken for MATLAB simulation of DSSC compensated system.

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1. INTRODUCTION

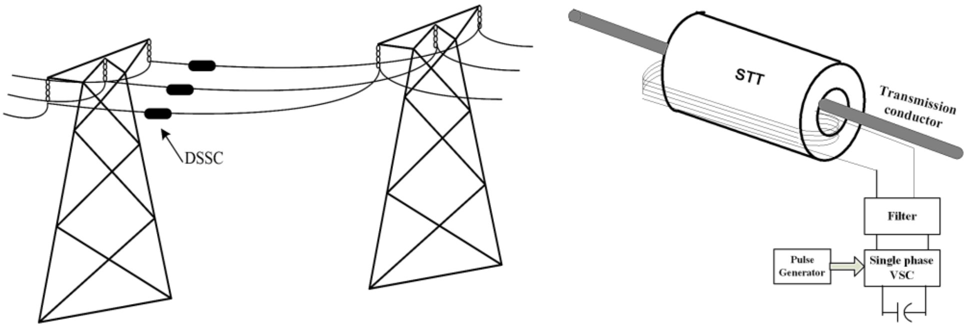
Power system operation and control in a secure manner is a major concern nowadays. Numerous new generating plants are commissioned and generate electricity to fulfil the load demand. Parallelly, power generation through renewable energy are provided with a great boost over worldwide. It also injects power in the exiting power grid. This total generated power is distributed to load by transmission network and distributed network. Because of increased power insertion in the grid, some lines may be overloaded and at the same time, some lines may be operating well below its thermal limit. Therefore, new lines need to be erected to avoid congestion in the existing grid. But due to the high cost of installation along with other problems such as environmental issues, long erection blocks, and land acquisition problems, it is not a feasible solution to avoid transmission line overloads. Flexible AC transmission system (FACTS) opens a new option to overcome this problem [1]. It helps to utilize transmission lines up to its full extent by altering bus voltage, line reactance, and power angle. There are many installations worldwide aiming at power flow control, power oscillation damping, reactive power management, and voltage stability. Different FACTS controllers are installed worldwide. These lumped FACTS device rating is very high and it is requiring high coupling transformer with high rated insulation base. Cost of power electronics device makes FACTS installation very costly. Voltage source converter (VSC) based FACTS devices are very costly and less reliable. In spite of wide control, VSC based FACTS controllers are not much popular due to its high cost of installation and operation and its reliability is also very less. A distributed FACTS concept overcame problems of lumped FACTS controller. A distributed FACTS concept was proposed with the aim of providing cost effective power flow control with increased reliability [2]. Distributed series reactors (DSR), distributed series impedances (DSI), and distributed static series compensator (DSSC) are some of the distributed FACTS devices to control power flow significantly [3]. A distributed power flow controller (DPFC) is one of the types of distributed series FACTS controller [4]. It is the device similar to unified power flow controller (UPFC) but it is without common DC link for series and shunt compensating controllers. It consists of multiple low power DSSC devices on the line with single static compensator (STATCOM). Active power required for series compensator at the DC terminals is provided by the line current with its third harmonic current injection. Similarly, a distributed power flow controller using emitter turn off (ETO) device is presented in [5]. It consists of modular self-powered converter connected with the line without coupling transformer. DSSC is employed for altering line reactance to control line current [6]. The use of DSSC can be employed to limit the fault current in the line. DSSC operation in inductive mode will increase effective line reactance and reduce the fault current [7]. A linearized DSSC modeling is presented in [8]. Distributed power flow controller using DSC is described for active power in the line and performance analysis is investigated [9], [10]. Voltage stability in DSSC compensated system is put up in the reference [11]. Many more research papers were published on the series compensation using DSSC [12]-[16].

Problem with the DSSC application is that large number of devices need to be connected in series with the line at regular intervals. With the application of optimization technique, number of DSSC devices can be chosen optimally to achieve active power control. Various literature is cited on optimal location of FACTS controllers solving multiobjective problem [17], [18]. Optimal coordinated operation of distributed static series compensators for wide-area network congestion relief is presented in [19]. Biogeography based optimization is used to find optimal location of distributed static series compensators [20]. Different objectives are formulated such as minimizing cost of installation, improving loading margin, minimizing voltage deviation considering different constraints. Optimal location of shunt-series FACTS controller is obtained by applying multiobjective optimization method. A mathematical optimization programming is formulated using Ɛ-constraint. Optimal location of phase shifting transformer (PST), hybrid flow controller (HFC), and UPFC is obtained along with their setting to attain multiobjective function [21]. Optimization aspect in DSSC compensated system to get maximum loadability and minimum reactive power generation is not addressed in the literature.

In the proposed work, DSSC is demonstrated for current control in the line. Many numbers of DSSC’s are optimally placed in the line to achieve two targets; first is to get maximum loadability index with optimum emulated reactance of DSSC’s and second is to minimize reactive power generation. In this work, two objective functions are optimally solved on DSSC compensated system. When DSSC devices in large number are connected in the line, a substantial alteration in the line current is found. Optimization technique is employed to find optimum usage of DSSC devices on optimal location of the device. A multiobjective optimization problem is formulated to maximize system loadability index and minimizing reactive power generation. A particle swarm optimization method is applied to solve the optimization. Paper is organized as follows: i) Section 1 gives introduction about the research carried out; ii) Section 2 is presented on DSSC construction and operation; iii) Section 3 covers flowchart and method of the proposed work in this paper; and iv) Section 4 presents system studies followed by result and conclusion. IEEE 14 bus test system is considered for studies. MATLAB software is used to validate the system studies.

2. DISTRIBUTED STATIC SERIES COMPENSATOR (DSSC)

DSSC is series connected low power device connected on each phase (~20 kVA) as shown in Figures 1(a) and 1(b). With the help of DSSC, a series compensation is realized. and it can be implemented on the line conductor directly. DSSC mainly constitutes a single-phase inverter. Input to inverter is given by voltage across DC link capacitor. High turns ratio STT is used to connect DSSC device in the existing line. STT core is wound on the transmission line conductor and it acts as winding of single turn transformer. On the other side of transformer, it consists of number of turns which steps down current in the inverter circuit. This drops down inverter cost. DSSC is a series connected compensator and it injects voltage in series with the line. Injected voltage at 90° leading or lagging to line current emulates inductive or capacitive reactance in series with the line reactance.



(a) (b)

Figure 1. DSCC: (a) suspended on line and (b) structure

2.1. Power flow equations incorporating DSSC

Series FACTS device SSSC modeling is given in [22], [23]. On similar lines, the modelling of DSSC is presented as a voltage source $V_{se}\angle\theta_{se}$. Considering DSSC connected on the line between bus i and j as given in Figure 2. P_{ij} and Q_{ij} power (with DSSC compensation) is given by:

$$P_{ij} = V_i^2 g_{ii} - V_i V_j [g_{ij} \cos(\theta_i - \theta_j) + b_{ij} \sin(\theta_i - \theta_j)] \\ -V_i V_{se} [g_{ij} \cos(\theta_i - \theta_{se}) + b_{ij} \sin(\theta_i - \theta_{se})] \quad (1)$$

$$Q_{ij} = -V_i^2 b_{ii} - V_i V_j [g_{ij} \sin(\theta_i - \theta_j) - b_{ij} \cos(\theta_i - \theta_j)] \\ -V_i V_{se} [g_{ij} \sin(\theta_i - \theta_{se}) - b_{ij} \cos(\theta_i - \theta_{se})] \quad (2)$$

DC link voltage is regulated through line itself. A small active power is taken from the line and it also provide converter losses.

$$Re(V_{se} I_{ji}^*) = -V_i V_{se} (g_{ij} \cos(\theta_i - \theta_{se}) - b_{ij} \sin(\theta_i - \theta_{se}) \\ +V_j V_{se} (g_{ij} \cos(\theta_j - \theta_{se}) - b_{ij} \sin(\theta_j - \theta_{se}) \quad (3)$$

Where $z_{ij} = g_{ij} + jb_{ij}$.

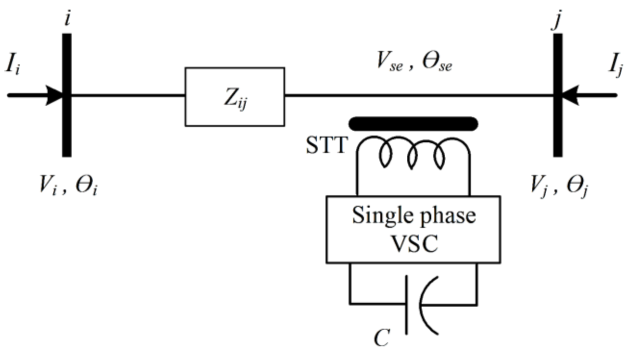


Figure 2. DSSC on the line between I and j bus

2.2. Problem formulation

Single unit of DSSC is a low power and light weight device. Due to low power, it will not give any significant change in active power. Therefore, multiple number of DSSC's are required to get a noticeable change in the line current is obtained. A work is proposed to find the location of DSSC device on the line optimally along with the enhanced loadability index. Minimum reactive power generation with optimum use of DSSC compensation devices is also proposed. Two objective functions are considered; one is to locate DSSC devices optimally with optimum use of the devices and second objective is to minimize reactive power generation.

2.2.1. Objective function

Objective function F_1 is framed to find maximum loadability index such that no line would be overloaded. Overload factor is characterized as I_L/I_L^{max}. Objective function F_1 is written in (4). I_L^{max} and maximum allowable current limit is represented by I_L and the actual current flow of i[th] transmission. *nl* represents number transmission lines. When the current exceeds than its thermal limit, factor F_1 will become more than 1. To avoid overloading of any of the line, F_1 should be less than 1 or equal to 1.

$$F_1 = \frac{1}{nl} \sum_{i=1}^{nl\Sigma} \left(\frac{I_{L_i}}{I_{L_i}{}^{max}} \right) \quad (4)$$

The Objective function F_2 is framed to get minimum reactive power generation. It is formulated as given in (5) where Q_{Gi} is the generated reactive power of i[th] generator.

$$F_2 = Q_{G_i} \quad (5)$$

2.2.2. Constraints

a) Equality constraint

The equality constraint is given as (6).

$$\sum_{i=1}^{ng} P_{G_i} - P_D - P_{Loss} = 0 \quad (6)$$

P_{Gi}: power generation by i[th] generator; P_D: total power demand; P_{loss}: transmission power losses; and *ng*: number of generators. (6) shows power balance equation. Bus i power is expressed as (7) and (8).

$$P_{G_i} - P_{D_i} - V_i \sum_{j=1}^{nb} (V_j [g_{ij} \, cos(\theta_i - \theta_j) + b_{ij} \, sin(\theta_i - \theta_j) = 0 \quad (7)$$

$$Q_{G_i} - Q_{D_i} - V_i \sum_{j=1}^{nb} (V_j [g_{ij} \, sin(\theta_i - \theta_j) + b_{ij} \, cos(\theta_i - \theta_j) = 0 \quad (8)$$

N-R power flow equations are solved. (9) shows power loss where g_k is the conductance of k[th] line, it is between buses i and j.

$$P_{Loss} = \sum_{k=1}^{nl} (g_k [g_{ij} \, cos(\theta_i - \theta_j) + b_{ij} \, sin(\theta_i - \theta_j) \quad (9)$$

b) Inequality constraints

The (10) and (11) show inequality constraints. Active power flow in the lines should not exceeds line thermal limit.

$$V_i^{\min} \le V_i \le V_i^{max} \text{ i =1, 2.....}n \quad (10)$$

$$Q_{G_i}^{min} \le Q_{Gi} \le Q_{Gi}^{max} \text{ i =1, 2....}ng \quad (11)$$

Inequality constraint display in (10) which shows generator bus voltages should be within acceptable ranges. Similarly, (11) reactive power generation acceptable limits.

c) FACTS constraints

Reactive power compensation by DSSC devices should be bounded. Compensation limit is fixed. For these studies, DSSC devices are bound to provide reactance emulation up to 50% of line reactance. In (12), X_{DSSC} is the DSSC's emulated reactance and X_{Line} is the line reactance.

$$\frac{x_{DSSC}}{x_{Line}} \le 0.5 \quad (12)$$

3. FLOWCHART AND METHOD

Flowchart of the proposed way to find optimal location of the DSSC devices to maximize system loadability index is shown in Figure 3. DSSC devices are implemented on each line and optimum emulated reactance is determined by using particle swarm optimization (PSO) so that all constraints are satisfied. Step by step loading is increased till maximum loadability index is reached. Procedure is continued for all the lines. System loadability index is tabulated and maximum loadability index is noted with the corresponding line with DSSC. This is the optimal location of DSSC device to achieve maximize system loadability index.

Similarly, Figure 4 shows flowchart of the proposed procedure to minimize reactive power generation. In this algorithm, DSSC is placed on each line and emulated reactance on concerned line is calculated using PSO with the main constraint that not a single line would cross its thermal limit. Process repeats for all the lines and results are tabulated indicating reactive power generation and concerned line with optimum emulated reactance by DSSC. From the table minimum reactive generation is noted along with corresponding line with emulated reactance. Considering both objective functions, a compromise solution is determined which gives optimal location of DSSC devices with optimum emulated reactance with maximum system loadability index and minimum reactive power generation. By considering results of both objective functions, a compromise solution is determined which gives optimal location of DSSC devices with optimum emulated reactance with maximum system loadability index and minimum reactive power generation.

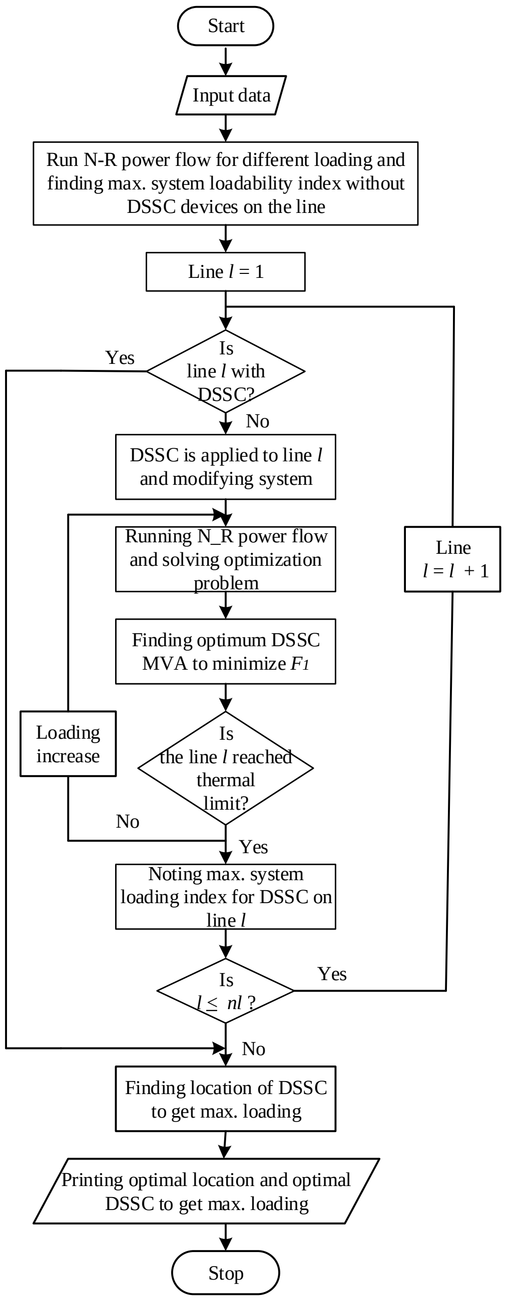


Figure 3. Flowchart of the proposed algorithm to maximize loadability index

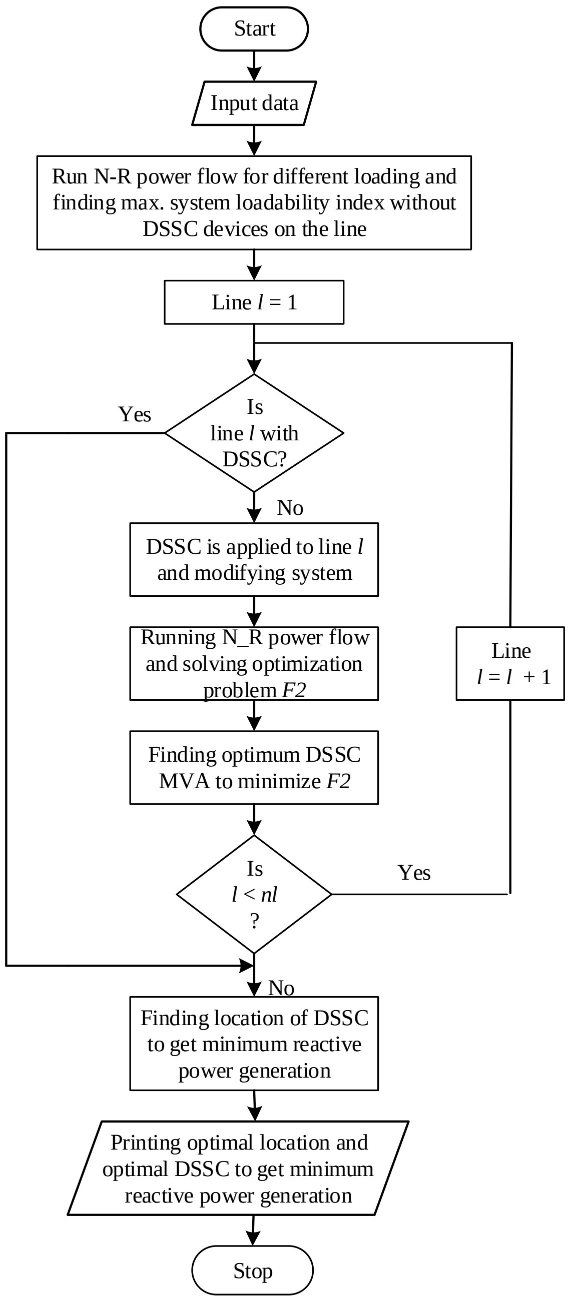


Figure 4. Flowchart of the proposed algorithm to minimize reactive power generation

4. SYSTEM STUDIES

In the present work, IEEE-14 bus system is considered to study DSSC on the power system in secured manner. MATPOWER is used for analysis [24]. IEEE system data is pulled from reference [25]. Five synchronous machines are shown. Three machines are exclusively for reactive power generation. Bus 1 is considered as slack bus. Generally, power transfer limit of transmission line is considered with respect to thermal limit of transmission conductor. A new formulation is proposed to find power transfer limit by demonstrating electro-thermal coupling effect of transmission line in [26]. Table 1 shows line thermal limit. Current flowing through the transmission line should not cross thermal limit. To get maximum loadability index, location of DSSC placement is determined optimally. Two regions are formed in IEEE-14 bus system. Buses 1 to 5 are considered in region I and it is selected for DSSC placement.

Table 1. Acceptable current (thermal rating) of lines [26]

Line		Current rating	Line		Current rating	Line		Current rating
From	To	(pu)	From	To	To	From	To	(pu)
1	2	1.64	5	6	1	10	11	0.36
2	3	1.83	4	7	1	6	12	0.33
2	4	1.64	7	8	0.41	6	13	0.33
3	4	1.45	4	9	1	12	13	0.22
1	5	1.83	7	9	0.41	9	14	0.36
2	5	1.64	9	10	0.41	13	14	0.33
4	5	1.64	6	11	0.33			

4.1. Base case results

Newton-Rhapson power flow equation is solved on test system without considering any compensation on the line. Reactive power generation is shown in Table 2. Active power loss is 13.59 MW and reactive power loss is 56.90 MVAR. System loadability index is calculated and it is equal to 1.08 without any compensation. Power flow shows that lines between bus 1-2 is handling more power and thermal limits of the line is very near. Similarly, lines connecting buses 1-5, 2-3, 2-4, 3-4, and 4-5 are found very vibrant to load variation.

Table 2. Reactive power generation

Gen Bus	Qgmin (MVAR)	Qgmax (MVAR)	Qg (MVAR)
1	Slack bus	Slack bus	-15.223
2	-40	50	47.928
3	0	40	27.758
6	-6	24	23.026
8	-6	24	21.03

4.2. DSSC employed to maximize system loadability index

The main purpose of this case is to achieve the highest system loadability index. To achieve this, the optimization problem is solved by finding the optimal use of DSSC with the highest loading. Objective is framed such that none of the line overloads. For secure power transfer, line would carry current well below its thermal rating. To ensure that all lines operate well below their thermal limit, the overload factor in (4) must be either less than or equal to 1. The algorithm shown in Figure 3 is applied to find optimal location for DSSC placement. DSSC is placed on any particular transmission line. Power flow is run and optimization problem is solved to find optimum reactance which is emulated by DSSC so that power transfer is within its limits. If no line is overloading, F1 is less than or equal to 1. In this condition, loadability index is increased stepwise and above steps are repeated. It is continued till maximum loadability index is obtained. At this index, all the lines are either below or equal to its rating. Optimum emulated reactance by DSSC placement on particular line with particular maximum loadability index is gained. Procedure repeated for DSSC compensation on all the lines.

Loadability indices along with optimum MVA by DSSC are calculated for all the lines. The optimal number of DSSCs are connected to each line and the maximum loadability index is observed. When DSSCs are on a specific line, Table 3 displays the maximum system loadability index achieved and the optimal reactance emulated by DSSC. According to base case N-R power flow statistics, current in lines 1-2 is increasing and it is getting close to its thermal limit. Without DSSC compensation, system loadability index is found 1.08. From Table 3 system loadability is obtained maximum when DSSC is implemented on line 1-5.

Table 3. Results of optimization problem F_1

Location of DSSC	Emulated reactance (pu)	Max loadability index	Q_{G2} (MVAR)	P_{Loss} (MW)	Q_{Loss} (MVAR)
1-2	0.0296	1.08	38.7861	16.3007	67.7098
1-5	0.0743	1.19	25.024	20.4314	77.4787
2-3	0.0651	1.17	35.64	15.8232	61.8143
2-4	0.0336	1.07	36.8737	16.1469	65.0936
2-5	0.0334	1.07	37.7276	16.0811	65.6367
3-4	0.0518	1.08	36.6937	16.4319	67.2516
4-5	0.0387	1.1	38.7161	17.1493	68.3285

4.3. DSSC for reactive power generation optimization

In IEEE-14 bus system, out of 5 reactive power generation sources, reactive power generation is maximum for the generator at bus 2. Therefore, the goal is to reduce the amount of reactive power generated at bus 2. While getting minimum reactive power generation, no transmission line would carry current more than its thermal limits. DSSC's are placed on each line in region I as given in flow chart. According to Table 4 result, the least reactive power generation at bus 2 will come from the DSSCs connected to buses 1-2.

Table 4. Results of optimization problem F_2

DSSC location	DSSC emulated reactance (pu)	Q_{G2} (MVAR)	P_{Loss} (MW)	Q_{Loss} (MVAR)
1-2	0.0295	34.86	14.26	49.07
1-5	0.1115	43.22	13.84	49.07
2-3	0.0989	44.12	13.61	50.67
2-4	0.0877	42.92	14.44	53.77
2-5	0.08481	46.30	14.09	55.18
3-4	0.0834	43.90	13.73	56.48
4-5	0.0830	43.92	13.73	56.49

4.4. Best compromise solution

When DSSC's are placed on the line from 1-5, it shows maximum loadability index 1.19 and minimum reactive power generation of generator at bus 2 is minimum when DSSC is placed on line from 1-2. Figure 5 shows overload factor when DSSC's are placed on line 1-5. Figure 6 shows reactive power generation optimization results at bus 2 when DSSC is placed on line 1-5. Best compromise solution is DSSC placement on the line connecting buses 1-5. It gives maximum loadability index and comparative less reactive power generation.

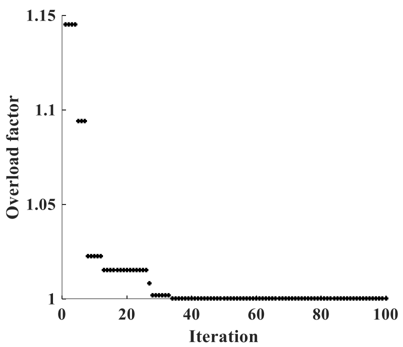


Figure 5. Overload factor (taking into account DSSC on lines 1–5) with maximum loading factor 1.19

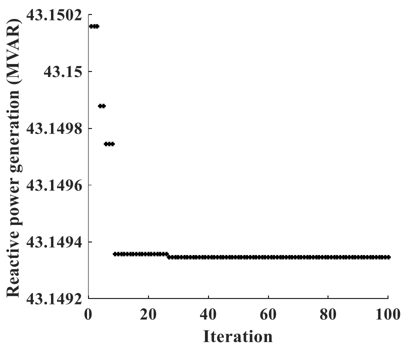


Figure 6. Reactive power generation at generator at bus 2 with DSSC on line 1-5

5. CONCLUSION

In this paper, multiobjective mathematical programming for optimal location of DSSC devices is developed using PSO technique. DSSC is low power inverter which is hanged on the existing line to achieve active power flow control through line. Two objective functions are considered to demonstrate optimal location of DSSC. First objective is formulated to increase loading margin and other objective is framed to reduce reactive power generation. A compromise solution is found out fulfilling both objectives and satisfying all the constraints. When DSSCs are placed on the line from bus 1 to bus 2, the minimum reactive power is produced by the generator at bus 2, and maximum system loadability is attained with DSSC compensation when DSSCs are placed on the line from bus 1 to bus 2.

It is feasible to select line from bus 1 to 5 for DSSC placement to get maximum loadability index as well as minimum reactive power generation. Results conclude that optimal location of DSSC devices with optimal emulated reactance increased the system loading margin as well as reduces generator reactive power generation.

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