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Genetic algorithm optimized impact assessment of optimally placed DGs and FACTS controller with different load models from minimum total real power loss viewpoint

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ABSTRACT

This paper presents the impact assessment of optimally placed different distributed generations (DGs) with different load models (DLMs) (such as DG-1, DG-2, DG-3 and DG-4) and flexible alternating current transmission system (FACTS) controller like static VAR compensator (SVC) by employing genetic algorithm (GA) in a distribution power systems (DPSs) from minimum total real power loss viewpoint. Different DPS performance indices such as minimization of real power loss, minimization of the reactive power loss, improvement of the voltage profile, reduction of the short circuit current or MVA line capacity and reduction of the environmental greenhouse gases like carbon dioxide (CO_2), sulphur dioxide (SO_2), nitrogen oxide (NO_x) and particulate matters in an emergency *e.g.* under fault, sudden change in field excitation of alternators or load increase in DPSs are considered. A comparison among different DGs with DLMs (such as DG-1, DG-2, DG-3 and DG-4) and FACTS controller like SVC is presented in this paper by employing GA. The effectiveness of the proposed methodology is tested on IEEE 37-bus distribution test system (38-node system). This paper clarifies the fact that, among the four types of DGs considered, DG-2 and DG-4 types of DGs at different operating power factors and FACTS controller like SVC offer better DPS performance indices when power factors varies from 0.80 to 0.99 leading and lagging, respectively. It is revealed that DG-2 type DG and SVC gives better DPS performance indices as compared to DG-1, DG-3 and DG-4 types DGs with DLMs and SVC. It is observed that DG-2 with SVC is more reliable and efficient as compared to the rest types of DG like DG-1, DG-3and DG-4 with SVC.

1. Introduction

According to [1], two major driving forces that created renewed interest in DGs are electrical market liberalization and environmental concerns. According to [2], the definition of DG goes like *DG is an electric power source connected directly to the distribution network or on the customer site of the meter.* In [2], it is defined as *a generator with small capacity close to its load that is not a part of a centralized generation system*. DG technologies include solar, wind turbines, fuel cells, small micro-sized turbines, wave energy, tidal energy, sea or ocean energy, bio-gas, diesel engine, geo-thermal energy, gas engine, sterling engine based generators and internal combustion engine generators *etc.* [3]. A study conducted by Electric Power Research Institute (EPRI) has indicated that by 2010, 25% of the new generation is to be DG [4]. A study initiated by Natural Gas Foundation indicated that this figure could be as high as 30% [4].

GA has been employed, in [5] by Singh and Goswami, to solve the optimal DG planning (ODGP) that maximizes the profit of the DNO by optimal placement of DG using GA. However, the limitation of GA is that it is more time consuming for large scale DPSs. Ramfrez-Rosado et al. [6] have presented the application of a new GA for optimal designing of large DPSs for solving the optimal sizing and location problem of feeders and substations using the corresponding fixed costs as well as the true nonlinear variable costs. It is applicable to single-stage or multi-stage distribution designs. GA methodology is implemented by Shaaban et al. in [7] to allocate renewable DG units optimally in

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Nomenclature

Abbreviation
BWL Buses without load
CON-INS-RES-COM-REF Constant-industrial-residential-commercial-reference load models, respectively
DISCO Distribution company
DLMs Different load models
DPSs Distribution power systems
DNO Distribution network operator
EIRI Environment impact reduction index
FACTS Flexible alternating current transmission systems
lg, ld Lagging and leading operating power factors of DGs
PLI, QLI Real and reactive power index, respectively
RLPM, RPM Real power and reactive power multiplier, respectively
SVC Static VAR compensator
SCCI Short circuit current or MVA line capacity index
VDI Voltage deviation index
WODG, WDG Without DG and with DG, respectively

Symbols
DG-1, DG-2, DG-3, DG-4 Different types of DGs
LOC_{DG} Location of DG
P_{DG}, Q_{DG} Real and reactive power delivered by DG, respectively
$P_{L\,\min}$, $Q_{L\,\min}$ Minimum real and reactive power losses, respectively
$P_{\mathrm{int}\,ake}$, $Q_{\mathrm{int}\,ake}$ Real and reactive power intake of main substation, respectively
PF_{DG} Power factor of DG
$S_{\mathrm{int}\,ake}$ Total MVA intake of main substation
S_{system} Total MVA of system
$\mathrm{SVC}_{\mathrm{alpha}}$ (α) Firing angle of SVC (α)
$\mathrm{SVC}_{\mathrm{MVAR}}$ Reactive power delivered/absorbed of SVC
$\mathrm{SVC}_{\mathrm{LOC}}$ Location of SVC
$V_{\max}$ Maximum value of bus voltage in p.u. (1.03)
$V_{\min}$ Minimum value of bus voltage in p.u. (0.95)
$alpha$, βeta Real and reactive power exponent values, respectively

distribution network and to maximize the worth of the connection to the local DISCO as well as to the customers connected to the system. Mohammad et al. [8] have proposed efficient hybrid GA and ant colony search algorithm for solving the optimal siting and sizing problem of DG and shunt capacitor banks simultaneously, based on imperialist competitive algorithm and GA. James et al. [9] have recently applied mixed-integer non-linear programming (MINLP) tools to the problem of optimal siting and sizing of DGs in DPSs. The MINLP approach is more time consuming for large scale DPSs as compared to other artificial intelligence (AI) based optimization techniques such as GA, particle swarm optimization (PSO), ant colony search (ACS) *etc*. This problem can be solved by using GA, PSO and ACS *etc*.

Celli et al. [10] have proposed a multi-objective formulation for the siting and sizing of DG resources into the existing DPSs. This type of methodology permits the planner to decide the best compromise between cost of network upgrading, cost of power losses, cost of energy not supplied and cost of energy required by the served customers. Sebastian et al. [11] have addressed the problem of simultaneous optimal allocation and sizing of dynamic VAR sources for short-term dynamic performance enhancement of DPSs. A heuristic optimization based approach is proposed in this work [11] with the aim of achieving a desirable performance under multiple contingencies with respect to a reference short-term voltage response.

Deng et al. [12] have presented the coordinated design of multiple FACTS supplementary damping controllers such as SVC and thyristor controlled series compensation (TCSC) to improve system small-signal stability by using real-time digital simulator. Novalio et al. [13] have presented a two-stage approach for solving the optimal voltage regulation problem in unbalanced radial distribution system in presence of photovoltaic generation by MINLP approach. The on-load tap changer (OLTC) and SVC have been considered as the voltage control devices in this work. Smith et al. [14] have proposed a novel approach for the solution obtained through GA and this result has been compared to actual optimal solution obtained through exhaustive solution. Gregorio et al. [15] have addressed the multi-stage expansion planning problem of DPSs where investments in the DPSs and in DGs are simultaneously considered.

Hegazy et al. [16] have used Monte Carlo approach to model the operating histories of the installed DGs. The problem of execution time associated with GA may be solved by Monte Carlo approach. El-Khattam et al. [17] have proposed a method of solving DG planning problem (location and size) in different utility scenarios as an optimization problem. The objective function of this work is based on supply-demand chain which is aimed at minimization of the investment and operating costs of local candidate DGs, payments towards purchasing the required extra power by the DISCO, payment towards loss compensation services as well as the investment cost of other chosen new facilities for different market scenarios.

Wang et al. [18] have proposed an analytical method to determine the best location of candidate DG for minimum loss configuration. Othman et al. [19] have presented an efficient and fast converging optimization technique based on some modifications of the traditional big bang-big crunch method for optimal placement and sizing of voltage controlled DGs. This algorithm deals with the optimization problems

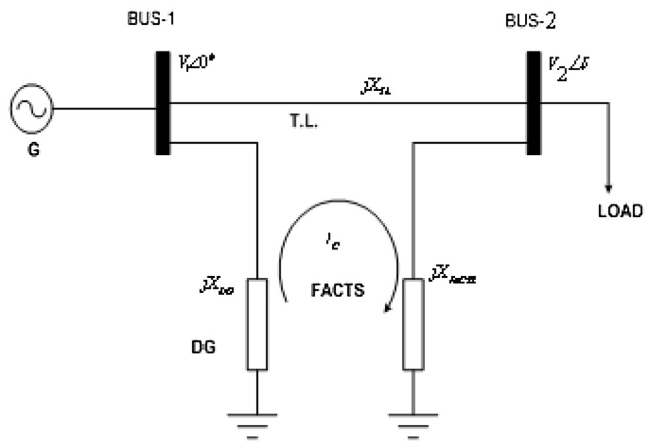

Fig. 1. Schematic diagram for optimal placement and properly coordinated control of DGs and FACTS controller in DPSs.

incorporating multiple DGs for the sake of power as well as energy loss minimization in balanced/unbalanced DPSs. The analytical methods are more time consuming for large scale DPSs as compared to AI based optimization techniques.

Injeti et al. [20] have proposed a novel approach, such as GA, to identify optimal access point and capacity of multiple DGs in small, medium and large scale radial distribution systems from different DPS performance viewpoints. Arash et al. [21] have proposed a novel approach such as modified PSO for optimal multi objective placement and sizing of multiple DGs and shunt capacitor banks by simultaneously considering the load uncertainty. However, it has been proven in the literature that GA is more time consuming for large scale DPSs and may ambush into local optima.

Bahram et al. [22] have proposed a new index to determine the optimal size and location of DG units, in order to minimize real power losses and enhance voltage stability margin considering load variations. A modified form of ICA method is used in [22] to solve the optimization problem. Araya et al. [23] have proposed the power semiconductor technologies (*i.e.* FACTS controllers such as SVC and static synchronous compensator (STATCOM)) and their penetration in the field of DPSs. Verma [24] has discussed about the control of SVC for improvement of dynamic stability and damping of torsional oscillations. Claudio and Faur [25] have presented the detailed steady state models of two FACTS controllers (namely, SVC and TCSC) to study their effects on the voltage collapse phenomena in DPSs. Farsangi et al. [26] have presented a method to seek the optimal location of several SVCs in a DPSs based on the concept of a primary function. Varma et al. [27,28] have presented a novel approach for utilizing photovoltaic and solar farm along with FACTS controller (such as STATCOM) to regulate the point of common coupling voltage during night time when the solar farm is not producing any real power. Singh et al. [29] have presented multi-objective planning of DG with different load models by GA.

In this paper, the power flow problem of a 38-node distribution test system is obtained in the following fashion. Different types of DG sizes are considered in the practical range (0–4.00 p.u.), decided by the total system demand (assumed as 3.9093 p.u.). The DG of 0 p.u. value corresponds to system without DG whereas 4.00 p.u. DG corresponds to a case when all the real power requirements are met by the DGs. It is considered that the DG is operated at unity power factor. Each bus of the system is considered for the placement of DG of given size from the range considered. The size of SVC considered for the practical range is −0.500 to +0.500 p.u. The bus voltage occurring outside the range 0.95–1.03 p.u. is treated as the case of voltage violation.

The concept of optimal placement and properly coordinated control of DGs and FACTS controller are discussed in the open literatures. The schematic diagram of interaction between DGs and FACTS controller is shown in Fig. 1. The frequency ranges of interactions between DGs and FACTS controller are given in Table A1 of Appendix Section.

Refs. [1–29] have discussed about the impact assessment of DPSs performance indices with single type of DG having different loading conditions such as static load models by applying different novel approaches (such as GA in [5–29]) and exhaustive search approach (such as deterministic approach in [28]). Literature review reveals that the investigation of the DPS performance indices of DPSs having different types of DGs (such as DG-1, DG-2, DG-3 and DG-4) with DLMs and FACTS controller like SVC has not been used in the open literature. Literature survey also unfolds that the investigation of DPS performance indices of DPSs having same kind of DG such as DG-2 and DG-4 at different operating power factors and FACTS controller like SVC with DLMs offer better DPS indices when power factors varies, respectively, from 0.80 to 0.99 leading and lagging. To the best knowledge of the authors of the present work, this type of work is yet to be addressed.

This paper considers all possible types of DGs (such as DG-1, DG-2, DG-3 and DG-4) with DLMs and FACTS controller like SVC for impact assessment of DPSs performance indices from minimum real power loss viewpoint by using GA. This paper also clarifies the fact that, among the four types of DGs considered, DG-2 and DG-4 types of DGs at different operating power factors and FACTS controller like SVC offer better DPS performance indices when power factors varies from 0.80 to 0.99 leading and lagging, respectively.

The organization of the rest of the paper is as follows: The next section discusses about the mathematical problem formulation of the present work. Section 3 discusses about the GA implementation part. Section 4 presents the multi-objective function formulation. In Section 5, simulation results and discussions are focussed. Finally, the conclusions of the present paper and future research scope are presented in Section 6.

2. Mathematical problem formulation

The different types of static load models and DGs and FACTS controller like SVC model are presented in this section as follows:

2.1. Type of static load models

To quantify the effect of different types of DGs and FACTS controller like SVC planning for DLMs scenarios (*i.e.* CON-INS-RES-COM-REF), an IEEE 37-bus DPS is adopted in this paper. In conventional load flow analysis, the real power and the reactive power loads are assumed as constant power load whereas, in practice, the loads may be voltage dependent *i.e.* industrial, residential, commercial and reference loads which may be represented by models, as described in [5]. The voltage dependent load model is a static load model that represents the DPS relationship to voltage as an exponential form and may be represented by (1) and (2)

$$P_{i\_bus} = P_{0i\_bus}\left(\frac{|V_{i\_bus}|}{|V_{0i\_bus}|}\right)^{alpha} \quad (1)$$

$$Q_{i\_bus} = Q_{0i\_bus}\left(\frac{|V_{i\_bus}|}{|V_{0i\_bus}|}\right)^{\beta eta} \quad (2)$$

where *alpha* and β*eta* are the real and reactive power exponents; P_{i_bus}, Q_{i_bus}, P_{0i_bus}, Q_{0i_bus}, V_{i_bus} and V_{0i_bus} are in per unit. The above two equations neglect the frequency dependence of distribution system load due to the fact that it is pan-system phenomenon which can not be controlled locally and remain the same for the whole system. In practice, the load on each bus may be the composition of industrial, residential, commercial and reference ones which may vary with seasonal day and night. Therefore, in [5], the different load models at each bus is considered and those are described in (3) and (4)

$$\begin{aligned} P_{i\_bus} = {} & w_{ins\_pi\_bus} \times P_{0i\_bus}\left(\frac{|V_i\_bus|}{|V_{0i\_bus}|}\right)^{alpha_{ins}} + w_{res\_pi\_bus} \times P_{0i\_bus}\left(\frac{|V_{i\_bus}|}{|V_{0i\_bus}|}\right)^{alpha_{res}} \\ & + w_{com\_pi\_bus} \times P_{0i\_bus}\left(\frac{|V_{i\_bus}|}{|V_{0i\_bus}|}\right)^{alpha_{com}} + w_{ref\_pi\_bus} \times P_{0i\_bus}\left(\frac{|V_{i\_bus}|}{|V_{0i\_bus}|}\right)^{alpha_{ref}} \end{aligned} \quad (3)$$

$$\begin{aligned} Q_{i\_bus} = {} & w_{ins\_qi\_bus} \times Q_{0i\_bus}\left(\frac{|V_{i\_bus}|}{|V_{0i\_bus}|}\right)^{\beta eta_{ins}} + w_{res\_qi\_bus} \times Q_{0i\_bus}\left(\frac{|V_{i\_bus}|}{|V_{0i\_bus}|}\right)^{\beta eta_{res}} \\ & + w_{com\_qi\_bus} \times Q_{0i\_bus}\left(\frac{|V_{i\_bus}|}{|V_{0i\_bus}|}\right)^{\beta eta_{com}} + w_{ref\_qi\_bus} \times Q_{0i\_bus}\left(\frac{|V_{i\_bus}|}{|V_{0i\_bus}|}\right)^{\beta eta_{ref}} \end{aligned} \quad (4)$$

where $V_{i_bus}$is the bus voltage with DG and FACTS controller like SVC; V_{oi_bus} is the nominal bus voltage without DG and FACTS controller like SVC; $alpha_{ins}$ and βeta_{ins}, $alpha_{res}$ and βeta_{res}, $alpha_{com}$ and βeta_{com}, $alpha_{ref}$ and βeta_{ref}, are the real power and the reactive power exponents for industrial, residential, commercial, reference load model, respectively; $w_{ins\_pi\_bus}$, $w_{res\_pi\_bus}$, $w_{com\_pi\_busand}$ $w_{ref\_pi\_bus}$ are the relevant factors for real power industrial, residential, commercial, reference load models at bus *i*, respectively; $w_{ins\_qi\_bus}$, $w_{res\_qi\_bus}$, $w_{com\_qi\_busand}$ $w_{ref\_qi\_bus}$ are the relevant factors for industrial, residential, commercial and reference load models at bus *i*, respectively. Eqs. (5) and (6) must be satisfied for all the buses except *buses without load* (BWL) (bus 1 is chosen as slack bus and buses 34–38 are not having any load [5]).

$$w_{ins\_pi\_bus} + w_{res\_pi\_bus} + w_{com\_pi\_bus} + w_{ref\_pi\_bus} = 1 fori = 1toN_B, buti \neq BWL \quad (5)$$

$$w_{ins\_qi\_bus} + w_{res\_qi\_bus} + w_{com\_qi\_bus} + w_{ref\_qi\_bus} = 1 fori = 1toN_B, buti \neq BWL \quad (6)$$

For example, the relevant factors of each load model at each bus are hypothetically generated. In this study, it is assumed that $w_{ins\_pi\_bus} = w_{ins\_qi\_bus}$, $w_{res\_pi\_bus} = w_{res\_qi\_bus}$, $w_{com\_pi\_bus} = w_{com\_qi\_bus}$, $w_{ref\_pi\_bus} = w_{ref\_qi\_bus}$. The values of these factors are given in Table A2 (refer Appendix Section). The values for exponents of voltage for real and reactive power component for constant, industrial, residential, commercial and reference load models are given in Table A3 of Appendix Section.

2.2. Impact of DGs and SVC on DPSs and its impact indices

2.2.1. Mathematical modelling of DG and SVC

(a)Different types of DGs: the technical issues related to DGs, however, may vary significantly with the rating of the DPSs. Therefore, it would be appropriate to introduce about the categories of DGs. Depending on the type and size. Table A4 (refer Appendix Section) depicts the existing categories of DGs. The four broad categories of DGs, on the basis of real and reactive power delivered/absorbed to/by the systems, are as follows [5]:

(i) DG-1 (named as T1): this type of DG is capable of delivering only the real power such as photovoltaic, micro turbines, fuel cells, bio-gas which are integrated to the main grid with the help of converters/inverters. However, according to current situation and grid codes, the photovoltaic may be (and in sometimes is) required to provide the reactive power as well so that only the real power is supplied at unity operating power factor.

(ii) DG-2 (named as T2): this type of DG is capable of delivering both the real power and the reactive power. DG units based on diesel engines as diesel generators and synchronous machines (cogeneration, gas turbine *etc.*) come under this type of DG. For it, both the real power and the reactive power are supplied at different operating power factors (*e.g.* 0.80–0.99 leading).

(iii) DG-3 (named as T3): this type of DG is capable of delivering only the reactive power. Synchronous compensators, capacitor bank, inductor bank, OLTC transformers, FACTS controller and gas turbines are examples of this type of DG and operate at zero power factor. So, only the reactive power is supplied at zero operating power factor for this type of DG.

(iv) DG-4 (named as T4): this type of DG is capable of delivering the real power but consumes the reactive power. Mainly, induction generators, which are used in wind farms fall, under this category. However, doubly fed induction generators may consume or produce reactive power *i.e.* operates similar to synchronous generators. Here, only the real power is supplied and the reactive power is drawn from the system at different operating power factors (*e.g.* 0.80–0.99 lagging).

The mathematical formulation of DGs and FACTS controller like SVC planning problem is proposed on the basis of two objective functions, as follows [5]:

(a) *Minimization of real power loss of the system*: this objective function is the minimization of the total real power loss (P_{Loss}) of the system. The P_{Loss} of the system is represented by (7).

$$P_{Loss} = \sum_{i,j \in N_L} \frac{{P_{ij\_bus}}^2 + {Q_{ij\_bus}}^2}{|V_{i\_bus}|^2} r_{ij\_bus} \tag{7}$$

The P_{Loss} is function of all the system bus voltage (V_{i_bus}), line resistances (r_{ij_bus}), *alpha* and β*eta*. The total losses, mainly, depend on voltage profile.

(b) *Minimization of total power intake at substation*: the objective function is apparent power intake (S_{int}) at main substation. The P_{intake} is the sum of P_{Demand} and P_{Loss} and is represented by (8).

$$P_{\text{int}ake} = P_1(V, P_0, Q_0, alpha, \beta eta) = P_{Demand} + P_{Loss}$$
$$= \sum_{i}^{N_B} P_{0i\_bus} \left(\frac{|V_{i\_bus}|}{|V_{0i\_bus}|} \right)^{alpha} + P_{Loss} \tag{8}$$

Similarly, Q_{intake} is the sum of Q_{Demand} and Q_{Loss} and is represented by (9).

$$Q_{\text{int}ake} = Q_1(V, P_0, Q_0, alpha, \beta eta) = Q_{Demand} + Q_{Loss} = \sum_{i}^{N_B} Q_{0i\_bus} \left(\frac{|V_{i\_bus}|}{|V_{0i\_bus}|} \right)^{\beta eta} + Q_L \tag{9}$$

Apparent power intake at main substation is expressed by (10)

$$S_{\text{int}ake} = \left[\left({P_{\text{int}ake}}^2 \right) + \left({Q_{\text{int}ake}}^2 \right) \right]^{1/2} \tag{10}$$

where $P_{\text{int}ake}$ and $Q_{\text{int}ake}$ are the real and the reactive power intake at main substation without DG and FACTS controller like SVC, respectively. The apparent power requirement for distribution system with DG and FACTS controller like SVC is expressed by (11)

$$S_{system} = \left[(P_{\text{int}ake} + P_{DG} + P_{FACTS}(\alpha))^2 + (Q_{\text{int}ake} \pm Q_{DG} \pm Q_{FACTS}(\alpha))^2 \right]^{1/2} \tag{11}$$

where P_{DG}&$P_{FACTS}(\alpha)$are the real power supported by DG and FACTS controller like SVC; and Q_{DG}&$Q_{FACTS}(\alpha)$are the reactive power supported/absorbed by DG and FACTS controller like SVC. It is observed that Eqs. (12) and (13) hold good for DPSs.

$$\sum_{i=1}^{N_B} P_0(|V_{i\_bus}|)^{alpha} > P_{Loss} \tag{12}$$

$$\sum_{i=1}^{N_B} Q_0(|V_{i\_bus}|)^{\beta eta} > Q_{Loss} \tag{13}$$

Thus, the values of P_{intake} and Q_{intake} are decided, mainly, by the load exponents *i.e. alpha* and β*eta*. The above objectives are subjected to the following set of power flow, line limit constraint, voltage limit and voltage step limit. The real and reactive power flows are defined as in (14)–(20).

$$P_{i\_bus} = \sum_{j=1}^{N_B} |V_{i\_bus}||V_{j\_bus}|[G_{ij\_bus} Cos(\delta_{i\_bus} - \delta_{j\_bus}) + B_{ij\_bus} Sin(\delta_{i\_bus} - \delta_{j\_bus})] \text{fori\_bus} = 1 \text{to} N_B \tag{14}$$

$$Q_{i\_bus} = \sum_{j=1}^{N_B} |V_{i\_bus}||V_{j\_bus}|[G_{ij\_bus} Sin(\delta_{i\_bus} - \delta_{j\_bus}) - B_{ij\_bus} Cos(\delta_{i\_bus} - \delta_{j\_bus})] \text{ fori\_bus} = 1 \text{to} N_B \tag{15}$$

$$P_{i,j\_bus} = |V_{i\_bus}|^2 G_{ij\_bus} - |V_{i\_bus}||V_{j\_bus}|[G_{ij\_bus} Cos\theta_{ij\_bus} - B_{ij\_bus} Sin\theta_{ij\_bus}] \text{ fori, j\_bus} \in N_L \tag{16}$$

$$Q_{i,j\_bus} = |V_{i\_bus}|^2 B_{ij\_bus} - |V_{i\_bus}||V_{j\_bus}|[G_{ij\_bus} Sin\theta_{ij\_bus} + B_{ij\_bus} Cos\theta_{ij\_bus}] \text{ fori, j\_bus} \in N_L \tag{17}$$

$$V_{\min} \le |V_{i\_bus}| \le V_{\max}, fori\_bus = 1toN_B \tag{18}$$

$$S_{ij\_bus} \le CS_{ij\_bus}^{\max}, fori, j\_bus \in N_L \tag{19}$$

$$V_{stepi\_bus} \le V_{step}^{\max}, fori\_bus = 1toN_B \tag{20}$$

(b) SVC – basic concept: according to IEEE CIGRE definition [24,25], *a static VAR compensator is a static VAR generator whose output is varied so as to maintain or control specific parameters (e.g. voltage or reactive power of bus) of the electric power system.*

SVC is a first generation FACTS controller that is already in operation at various places in the world. In its simplest form, it uses a thyristor controlled reactor (TCR) in conjunction with a fixed capacitor (FC) or thyristor switched capacitor (TSC). A pair of opposite poled

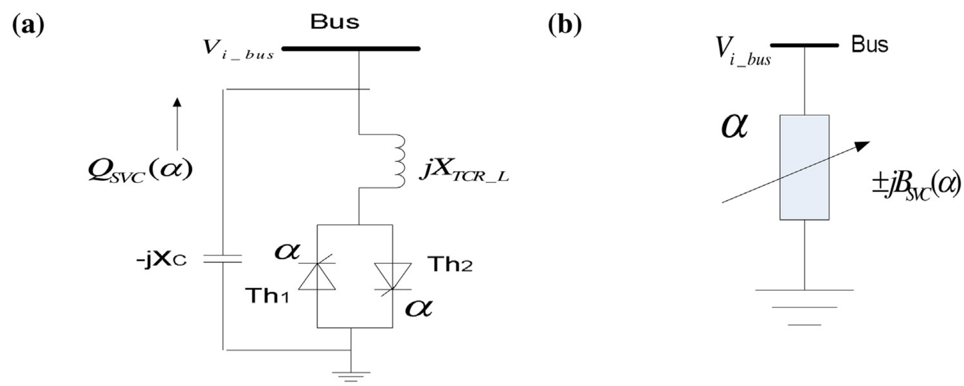

Fig. 2. SVC (a) firing angle model and (b) total susceptance model.

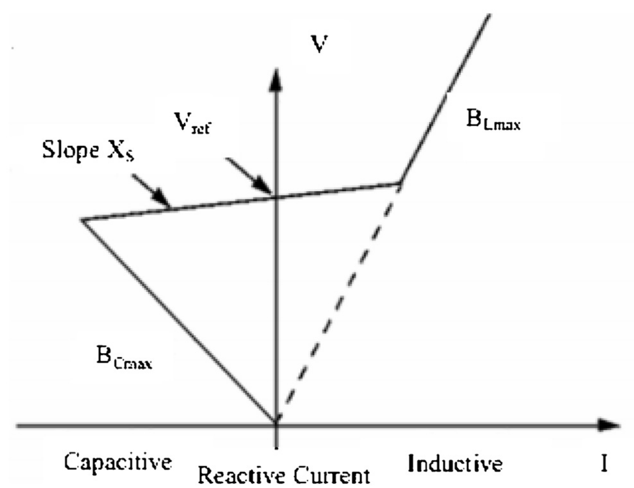

Fig. 3. The V-I characteristics of SVC.

thyristors (back to back) is connected in series with a fixed inductor to form a TCR module while the thyristors are connected in series with a capacitor to form a TSC module. An SVC can control the voltage magnitude at the required bus and, thereby, improves the voltage profile of the system. The primary task of an SVC is to maintain the voltage of a particular bus by means of reactive power compensation as shunt mode compensation (obtained by varying the firing angle of the thyristors). It may also provide increased damping to power oscillations or vibrations and enhances power flow over a line by using auxiliary signals such as line real power, line reactive power, line current and computed internal frequency [24,25]. The SVC is also known as reactive power supporter device. SVC is a shunt connected FACTS controller whose main functionality is to regulate the voltage at a given bus by controlling its equivalent reactance (X_{SVC}). Basically, it consists of a fixed capacitor (FC) and a TCR in parallel fashion. Generally, there are two configurations of SVC models (refer shown in Fig. 2(a) and (b)).

(i) *Total susceptance model of SVC scenario*: a changing susceptance ($B_{SVC}(\alpha)$) represents the fundamental frequency equivalent susceptance of all the shunt modules making up the SVC, as shown in Fig. 2(a).
(ii) *Firing angle model of SVC scenario*: the effective reactance ($X_{effective\_SVC}(\alpha)$), which is function of changing firing angle α, is made up of the parallel combination of a TCR equivalent admittance and a fixed capacitive reactance (X_{FC}), as shown in Fig. 2(b). This model provides information about the SVC firing angle required to achieve a given level of compensation.

Fig. 3 shows the steady-state and the dynamic voltage-current characteristics of the SVC. In the active control range, current/susceptance and reactive power are varied to regulate voltage according to the slope (droop) characteristic. The slope value depends on the desired voltage regulation, the desired sharing of reactive power production between various sources and other needs of the system. The slope is, typically, 1–5%. At the capacitive limit, the SVC becomes a shunt capacitor. At the inductive limit, the SVC becomes a shunt reactor (the current or reactive power may also be limited).

SVC firing angle model is only implemented in this paper. Thus, the model may be developed with respect to a sinusoidal voltage. The differential and the algebraic equations may be written as$I_{SVC}(\alpha) = -jB_{SVC}(\alpha)V_{i_bus}$. The fundamental frequency TCR equivalent reactance ($X_{TCR}(\alpha)$) is given in (21)

$$X_{TCR}(\alpha) = \frac{\pi X_{TCR\_L}}{\mu - \sin\mu} \tag{21}$$

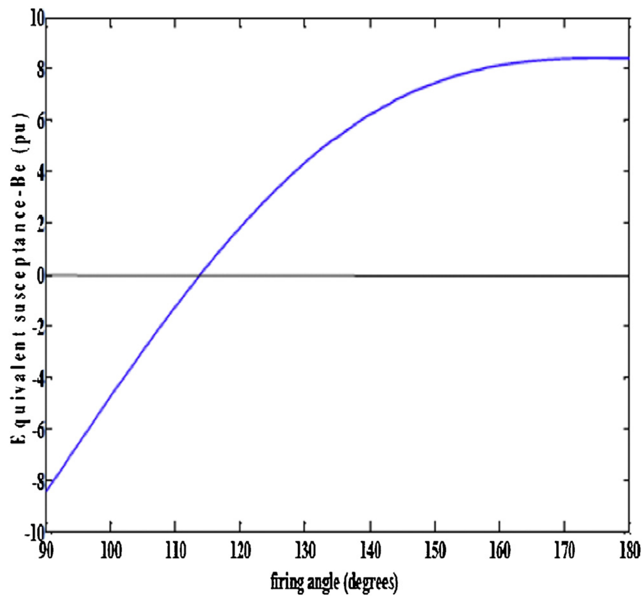

Fig. 4. SVC equivalent susceptance profile.

where $\mu = 2(\pi - \alpha)$, $X_{TCR\_L} = 2\pi fL$ and it may be expressed in terms of firing angle, as in (22)

$$X_{TCR}(\alpha) = \frac{\pi X_{TCR\_L}}{2(\pi - \alpha) + \sin 2\alpha} \tag{22}$$

where $\mu$and $\alpha$are the conduction and the firing angles, respectively.

At $\alpha = 90^o$, TCR conducts fully and the equivalent reactance ($X_{TCR}(\alpha)$) becomes X_{TCR_L}, while at$\alpha = 180^o$, TCR is blocked and its equivalent reactance becomes infinite. The SVC effective reactance ($X_{effective\_SVC}(\alpha)$) is determined by the parallel combination of X_{FC} and$X_{TCR}(\alpha)$ and is given by (23) and (24)

$$X_{effective\_SVC}(\alpha) = \frac{\pi X_{FC} X_{TCR\_L}}{X_{FC}[2(\pi - \alpha) + \sin 2\alpha] - \pi X_{TCR\_L}} \tag{23}$$

where $X_{FC} = {}^1\!/\!{}_2\pi fC$

$$Q_{FACTS}(\alpha) = Q_{SVC}(\alpha) = -V_{i\_bus}{}^2 \left\{ \frac{X_{FC}[2(\pi - \alpha) + \sin 2\alpha]}{\pi X_{FC} X_{TCR\_L}} \right\} \tag{24}$$

The SVC equivalent reactance is given in the above equation. It is shown in Fig. 4 that the SVC equivalent susceptanc ($B_{SVC} = -1/X_{SVC}$) profile (as function of firing angle) does not present discontinuities *i.e.* B_{SVC} varies in a continuous and smooth fashion in both the operative regions. Hence, linearization of the SVC power flow equations (based on $B_{SVC}$with respect to the firing angle) will exhibit a better numerical behaviour than the linearized model based onX_{SVC}. The real power delivered by SVC in all modes of operations is always taken as zero (*i.e.*$P_{FACTS}(\alpha) = P_{SVC}(\alpha) = 0$).

The initialization of the SVC variables is based on the initial values of AC variables and the characteristic of the equivalent susceptance (refer Fig. 4) and, thus, the impedance is initialized at the resonance point $X_{TCR}(\alpha) = X_{FC}$, *i.e.* $Q_{SVC}(\alpha) = 0$, corresponding to firing angle of SVC of near about 115° (approximate value is 113.82°) for the chosen parameters of L and C *i.e.* $X_{TCR_L}$is 0.1134Ω and $X_{FC}$is 0.2267Ω [25].

The modes of operation of SVC are as follows:

(i) SVC *behaves as a load mode*: SVC behaves as a load mode means that reactive power is absorbed from the system when the firing angle of SVC is 115.44°,
(ii) SVC *behaves as a generator mode*: SVC behaves as generator mode means that reactive power is delivered to the system when the firing angle of SVC is 112.25° and
(iii) SVC *behaves as a resonance mode*: SVC behaves as a resonance mode means that reactive power is neither delivered nor absorbed from the system when the firing angle of SVC is 113.82°

The values of different firing angles of SVC and its corresponding reactive power delivered/absorbed are given in Table A5 of Appendix Section.

2.2.3. DPS performance indices

The different considered power system performance are defined as follows [4–22].

(i) *Real power loss index (PLI)*: the real power loss index is defined by (25)

$$PLI = \frac{|P_{Loss\_WDG\_FACTS}|}{|P_{Loss\_WODG\_FACTS}|} \times 100\% \tag{25}$$

where$P_{Loss_WDG_FACTS}$ is the real power loss with DG and FACTS controller like SVC and $P_{Loss\_WODG\_FACTS}$ is the real power loss without DG and FACTS controller like SVC. The lower value of this index indicates that a better benefit in terms of real power loss reduction has occurred due to the DG and FACTS controller like SVC placement and sizing.

(ii) *Reactive power loss index (QLI)*: the reactive power loss index is defined as in (26)

$$QLI = \frac{|Q_{Loss\_WDG\_FACTS}|}{|Q_{Loss\_WODG\_FACTS}|} \times 100\% \tag{26}$$

where $Q_{Loss\_WDG\_FACTS}$ is the reactive power loss with DG and FACTS controller like SVC and $Q_{Loss\_WODG\_FACTS}$ is the reactive power loss without DG and FACTS controller like SVC. The lower value of this index indicates that a better benefit in terms of reactive power loss reduction has occurred due to the DG and FACTS controller like SVC placement and sizing.

(iii) *Voltage deviation index (VDI)*: one of the advantage of proper placement and sizing of different types of DGs and FACTS controller like SVC is the improvement in voltage profile. This index penalizes the size-location pair which gives higher voltage deviations from the nominal one (V_1 = 1.03 p.u.). In this way, closer the index to zero value, better is the network performance. It is related to the maximum voltage drop between each node and root node. The *VDI* may be defined as in (27)

$$VDI = \max\left(\frac{|\overline{V}_1| - |\overline{V}_{i\_bus\_DG}|}{|\overline{V}_1|}\right) \times 100\% for i\_bus = 2 to N_B \tag{27}$$

where$\overline{V}_1$ is the slack bus voltage and $\overline{V}_{i\_bus\_DG}$ is the voltage at *i*th bus with DG and FACTS controller like SVC. The lower value of this index indicates better performance of DPSs. Normally, the voltage limits ($V_{\min} \le V_{i\_bus} \le V_{\max}$) at a particular bus is taken as technical constraint and, thus, the value of VDI is, normally, small and within the permissible limits.

(iv) *Short circuit current or MVA line capacity index (SCCI)*: the power flow may diminish in some section of the network and release more capacity with the power supplied nearer to the load. This index is defined by (28)

$$SCCI = \max\left(\frac{|\overline{S}_{ij\_bus\_WDG\_FACTS}|}{|\overline{CS}_{ij\_bus}|}\right) \times 100\% for ij\_busset = 1 to N_L \tag{28}$$

where $\overline{CS}_{ij\_bus}$ is the MVA line capacity without DG and FACTS controller like SVC, $\overline{S}_{ij\_bus\_DG}$ is the MVA line capacity with DG and FACTS controller like SVC. As a consequence of supplying power near to the loads, MVA flows may diminish in some sections of the network and, thus, releasing more capacity. But in other sections, these may also increase to a level beyond distribution line limits (if line limits are not taken as constraints). This index provides important information about the level of power flows/currents through the network regarding maximum capacity of the distribution lines.

This gives the information about the requirement of system line up-gradations. Values higher than unity (calculated MVA flow values higher than the MVA capacity) of this index give the amount of capacity violation in term of line flows, whereas the lower values indicate the availability of the capacity.

The benefit of placing of different types of DGs and SVC in a system in the context of line capacity released is measured by finding the difference in SCCI between system with and without DG and SVC. The avoidance of flow near to the flow limit is an important criterion as it indicates that how earlier the system needs to be upgraded and, thus, adding to the cost. The use of SCCI index may not be applicable in the context available transmission capacity improvement in transmission systems.

Normally, the limit ($S_{(i,j\_bus)} \le S_{(i,j\_bus)\max}$) at a particular line is taken as a strict constraint and, thus, the value of SCCI is always positive. Lower value of this index indicates that more capacity is available. Index values more than 100% indicate that the lines are overloaded.

(v) *Environmental impact reduction index (EIRI)*: another potential benefit of DG and SVC is the production of energy with minimal greenhouse gas (GHG) emissions and other pollutants as compared to the conventional technologies. Concerns about greenhouse effect are growing rapidly in the public domain. Greenhouse effect is a result of rising in levels of carbon dioxide and other GHG emissions. It is believed that greenhouse effect will lead to global warming and world-wide climate change. Introduction of DG and FACTS controller like SVC will result in reduction of capacity needs of conventional plants due to two reasons *viz.* (a) the real power generated by the DG and the FACTS controller like SVC units will directly reduce the output requirements and (b) the resulting line loss reduction will further decrease the output needs from the conventional plants. The basic idea behind the EIRI (defined later in (32)) is to compare the emission of a particular pollutant with and without the employment of DG and FACTS controller like SVC. This is defined for the *i*th pollutant (CO_2, SO_2, NOx, *etc.*) by (29) [28].

$$EIR\_Index^k_{i\_pollutant} = \frac{|PE_{iw\_WDG\_FACTS}|}{|PE_{iw\_WODG\_FACTS}|} \times 100\% \tag{29}$$

where$PE_{pw_WDG_FACTS}$ and $PE_{pw\_WODG\_FACTS}$ are the amounts of emissions with and without DG and FACTS controller like SVC, respectively, for the *i*th pollutant and these are defined, in order, as in (30) and (31)

$$PE_{iw\_WDG\_FACTS} = \sum_{r=1}^{N_G}(EG)_{Br}(AE)_{ir} + \sum_{s=1}^{N_{DG}}(EDG)_s(AE)_{is} + \sum_{t=1}^{N_{FACTS}}(EFACTS)_t(AE)_{it} \tag{30}$$

$$PE_{iw\_WODG\_FACTS} = \sum_{r=1}^{N_G}(EG)_r(AE)_{ir} \tag{31}$$

where $(EG)_{Br}$ and $(EG)_r$ are the amounts of electrical energy generated by the *m*th conventional power plant with and without the employment of the DG and FACTS controller like SVC, respectively (MWh); $(AE)_{ir}$is the amount of emission of the *i*th pollutant for the *r*th conventional plant per MWh of energy generated and N_G is the total number of conventional generators in the system; $(AE)_{is}$is the amount of emission of the *i*th pollutant for the *s*th DG power plant per MWh of energy generated; $(AE)_{it}$ is the amount of emission of the *i*th pollutant for the tth FACTS controller like SVC power plant per MWh of energy generated; $(EDG)_s$ is the amount of energy generated by the sth DG plant (MWh) and $N_{DG}$is the total number of DG plants in the system; $(EFACTS)_t$ is the amount of energy generated by the tth FACTS controller like SVC plant (MWh) and $N_{FACTS}$is the total number of FACTS controller plants in the system. Once again, the loads supplied at different buses are assumed to be the same in both cases *i.e.*with and without DG. In reality, power plants emit many pollutants into the atmosphere. Thus, it is useful to define a composite index to include all the major associated pollutants. This index (termed as EIRI) may be formulated as in (32)–(34)

$$EIRI = 1 - \sum_{i=1}^{N_i} (EI)_i \times (EIR\_Index^{k}_{\mathrm{i\_pollutant}}) \tag{32}$$

with

$$0 \le (EI)_i \le 1 \tag{33}$$

and

$$\sum_{i=1}^{N_i} (EI)_i = 1 \tag{34}$$

where$(EI)_i$ is the weighting factor for the ith pollutant andN_i is tha total number of pollutants of interest. The details of important pollutants emission levels of conventional generators and DGs and SVC such as carbon dioxide (CO_2), sulphur dioxide (SO_2), nitrogen oxide (NO_x) and particulate matters are given in Tables A6 and A7, respectively, of Appendix Section.

Table A8 (refer Appendix Section) shows the value for the weights used in present work, considering normal operation analysis and is similar to [28]. However, these values may vary according to an engineer's concern. In this analysis, CO_2 emission receives the first significant weight (as 0.40). The SO_2 emission receives the second significant weight (as 0.3). The NO_x emission receives the third significant weight (as 0.2). The particulate matters emission receives the fourth significant weight (as 0.1).

The selection of weighting factors for different pollutants in the EIRI are taken in this work on the merit/priority basis such as environmental criteria and indicators (*i.e.* resources, climate change, impact on ecosystems and wastes); economic criteria and indicators (*i.e.* impact on customers, impact on the overall economy, impacts on the utility and operation); and social criteria and indicators (*i.e.* security/reliability of energy provision, political stability and legitimacy, social and individual risks and quality of human life).

3. GA implementation

3.1. General

GA was invented by John Holland in the 1960s and was developed by Holland and his students and colleagues at the University of Michigan in the 1960s and the 1970s. In contrast with evolution strategies and evolutionary programming, Holland's original goal was not to design algorithms to solve specific problems, rather to formally study the phenomenon of adaptation as it occurs in the nature and to develop ways in which the mechanisms of natural adaptation might be imported into computer systems.

GA [3–23] is a search technique used for computing true or approximate solutions of optimization and search problems such as DG planning as well as DG and FACTS controller like SVC planning. The basic concept of GA is to simulate processes in natural system necessary for evolution, specifically, for those that follow the principles first laid down by Charles Darwin of survival of the fittest.

Reasons of using GA for different types of DGs (such as DG-1, DG-2, DG-3 and DG-4) and FACTS controller like SVC planning are as follows: GA

(i) is better optimization technique than conventional AI based techniques,
(ii) is more robust (*i.e.* performs very well for large scale optimization problems),
(iii) can solve multi-dimensional, non-differential, non-continuous and even non-parametrical problems,
(iv) is a method which is very easy to understand and it, practically, does not demand the knowledge of mathematics,
(v) can quickly scan a vast solution set,
(vi) can be easily interfaced to the obtainable simulations and models,
(vii) provides a list of optimal variables, not just a single solution,
(viii) optimizes with continuous or discrete variables,
(ix) deals with a large number of variables and
(x) can works with numerically generated data, experimental data, or analytical functions.

PSO is a relatively recent heuristic search method whose mechanism is inspired by the swarming or collaborative behaviour of biological populations. PSO is similar to GA in the sense that these two evolutionary heuristics are population-based search methods. In other words, PSO and GA move from a set of points (population) to another set of points in a single iteration with likely improvement using a combination of deterministic and probabilistic rules. GA and its many versions have been popular in academia and in industry, mainly, because of its intuitiveness, ease of implementation and the ability to solve effectively highly nonlinear, mixed integer optimization problems that are typical of complex engineering systems. The drawback of GA is its expensive computational cost. PSO has the same effectiveness (finding the true global optimal solution) as the GA but with significantly better computational efficiency (less function evaluations). The comparisons between GA, PSO and ACO techniques are presented in Table A9 of Appendix Section. From this table, it may be observed that GA techniques are more suitable as compared to PSO and ant colony optimization (ACO) for large scale distribution power system with DGs and FACTS controller since it convergences rapidly.

3.2. Basic GA operators

There are three simple operators in GA, namely, *selection, recombination* or *crossover* and *mutation* [1–22]. Taken *selection, crossover and mutation* together, it is called reproduction which is analogous to biological *crossover* and *mutations* [1–5]. These operators are discussed in brief as follows:

(i) *Selection*: selection attempts to apply pressure upon the population in a manner similar to that of natural selection that is found in biological systems. Poor performing individuals are weeded out and better performing (or fitter) individuals have a greater than average chance of promoting the information they contain within the next generation. This operator selects chromosomes in the population for reproduction. The fitter the chromosome, the more times it is likely to be selected to reproduce.
(ii) *Crossover*: crossover allows solutions to exchange information in a way similar to that used by a natural organism undergoing sexual reproduction. One method (termed as single point crossover) is used to choose pairs of individuals promoted by the selection operator. Randomly choose a single locus (point) within the binary strings and swap all the information (digits) to the right of this locus between the two individuals. Crossover probability is taken as 0.95 in the present work.
(iii) *Mutation*: mutation is used to randomly change (flip) the value of single bits within individual strings. Mutation is, typically, used very sparingly. In the present work, mutation probability is chosen as 0.15.

3.3. GA implementation

In this paper, GA (developed in the previous works of [5–22]) has been implemented for finding the best solutions of the multi-objective performance index function (MOBPIF) optimization task.

The first important aspect of correct GA implementation is the examination of potential solution. If the network structure is fixed, all the branches between buses are known and the evaluation of the objective function depends only on the size and the placement of different types of DGs (such as DG-1, DG-2, DG-3 and DG-4) and single FACTS controller like SVC. For this reason, each solution is examined for proper placement and corresponding size of different types of DGs (such as DG-1, DG-2, DG-3 and DG-4) and single FACTS controller like SVC unit.

The implementation of GA starts with randomly generating an initial population of the possible solutions. For each solution, size of DGs and single FACTS controller like SVC and placement (bus) are generated by the planner with economical and technical justifications. A number of size-placement pairs are randomly chosen until the total power loss of the system is optimal (or near optimal) for DGs and single FACTS controller like SVC penetration level. At this point, objective function is evaluated for verifying all the technical constraints. If any one of these is violating, then such a solution is rejected.

Once population cycle is initialized, the genetic operators are, repeatedly, applied in order to produce new solutions. By applying crossover and mutation operators, new population is generated. If any one of the technical constraints is violated or the DGs and single FACTS controller like SVC size and/or placement exceeds the limit, then the new solution is rejected.

Finally, according to GA theory, the new population is formed comparing the old and the new solutions and choosing the best among them. The algorithm stops when the maximum number of generations is reached or difference between objective function value of the best and the worst individuals becomes smaller than the specified value.

The various steps of GA for optimal placement of different types of DGs (such as DG-1, DG-2, DG-3 and DG-4) and FACTS controller like SVC with DLMs in DPSs from minimum total real power loss viewpoint are as follows:

Step 1: *Read the data*: read the IEEE 37-bus distribution system data, different load models data (*i.e.* CON-INS-RES-COM-REF), different types of DGs data (such as DG-1, DG-2, DG-3 and DG-4) and SVC data.

Step 2: *Run load flow for base case (initial fitness solution)*: run load flow for base case (initial fitness solution) and calculate the power system performance indices such as PLI, QLI, VDI, SCCI and EIRI for base case. Register the base case (initial fitness solution) characteristic.

Step 3: *Binary coding*: binary coding of the IEEE 37-bus distribution system data, different load models data (select one load model at a time *i.e.* CON-INS-RES-COM-REF) and different types of DGs data (select one DG at a time *i.e.* DG-1, DG-2, DG-3 and DG-4, respectively) and single FACTS controller like SVC.

Step 4: *Initialization*: generate the random population of n chromosomes (suitable solutions for the problem), randomly generate size-placement pairs of different types of DGs (*i.e.* select one DG at a time among DG-1, DG-2, DG-3 and DG-4) and single FACTS controller like SVC with DLMs (*i.e.* select one load model at a time *i.e.* CON-INS-RES-COM-REF) in a predefined range of size-placement of different types of DGs and single FACTS controller like SVC.

Step 5: *Fitness function value*: evaluate the fitness function value $[f(x)]$ of each size-placement of different types of DGs (such as DG-1, DG-2, DG-3 and DG-4) and single FACTS controller like SVC (chromosome) in the population, run load flow and calculate power system performance indices such as PLI, QLI, VDI, SCCI and EIRI for each size-placement pairs under uniform loading condition. Record the power system performance indices and its corresponding size-placement pairs.

Step 6: *New population*: create a new population by repeating following steps until the new population is complete:

(i) *Selection*: select two parent chromosomes from a population according to their fitness (better the fitness, bigger is the chance to be selected).
(ii) *Crossover*: with a crossover probability, the parent crossover to form a new offspring (children). If no crossover is performed, offspring would be an exact copy of the parent.
(iii) *Mutation*: with a mutation probability method, new offspring (children) mutates at each locus (position) in chromosome.
(iv) *Accepting*: place new offspring in a new population. Does it satisfy the constraints such as power flow conservation limits, distribution line thermal capacity limit and voltage deviation limit? Otherwise, repeat Step 6.

Step 7: *Replacement*: use newly generated population for a further run of the algorithm. Run load flow and calculate the new fitness solution for each size-placement pairs of different types of DGs (such as DG-1, DG-2, DG-3 and DG-4) and single FACTS controller like

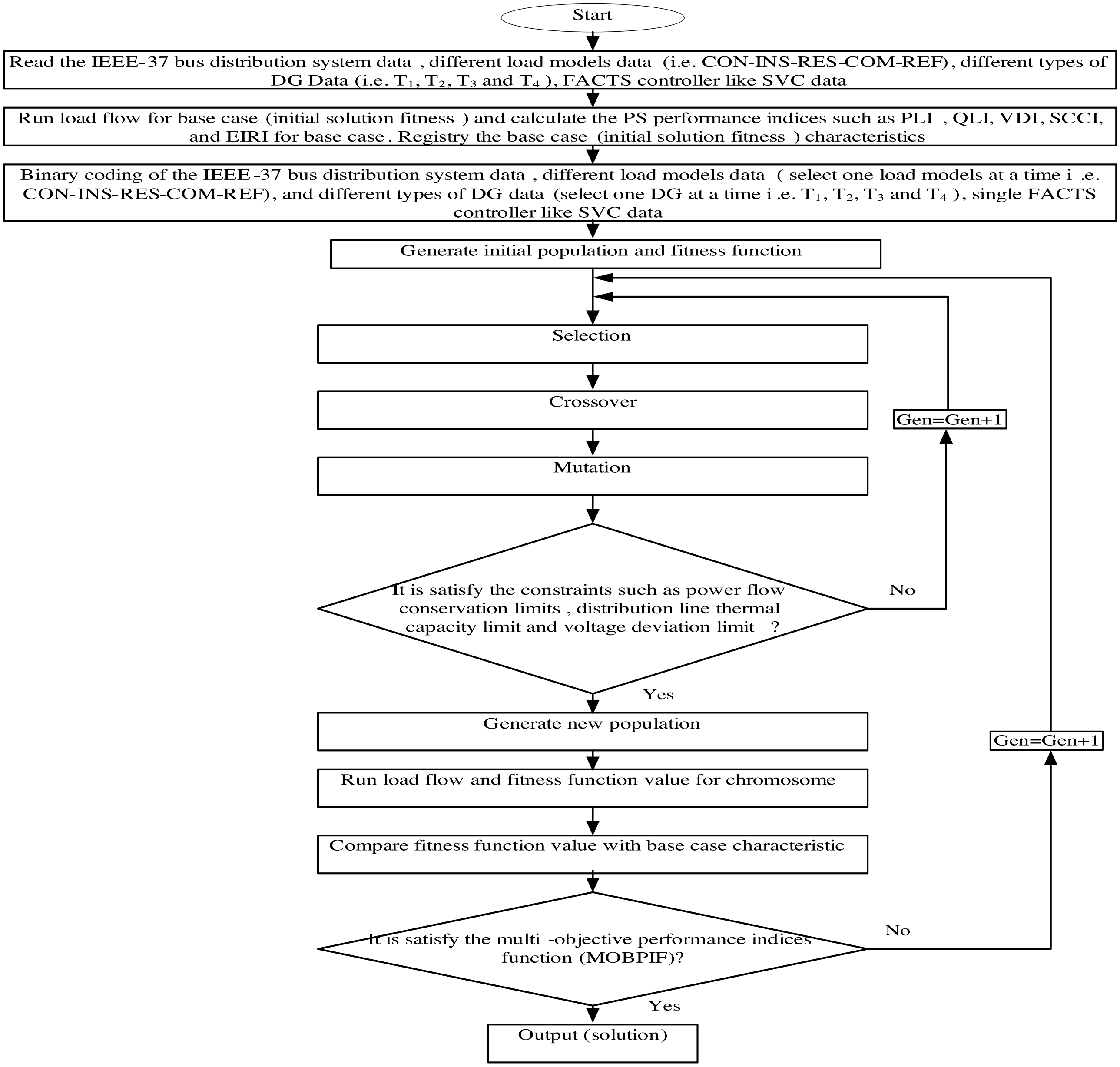

Fig. 5. Flowchart of GA for impact assessment of optimally placed different types of DGs and FACTS controller like SVC with DLMs in DPSs from minimum total real power loss viewpoint.

SVC (chromosome). Also, calculate the corresponding DPS performance indices such as PLI, QLI, VDI, SCCI and EIRI. Compare new fitness solution with base case (initial fitness solution) characteristic.

Step 8: *Test*: if one of the stopping criteria is satisfied then stop and retain the best solution in the current population.

Step 9: *Loop*: use the new generated population size *i.e.* offspring and parents as new generation. Does it satisfy the MOBPIF minimization criterion? Otherwise, set generation count $Gen = Gen + 1$. Go to Step 6.

The flowchart for the proposed methodology *i.e.* GA for impact assessment of optimally placed different types of DGs and single FACTS controller like SVC with DLMs in DPSs from minimum total real power loss viewpoint is presented in Fig. 5.

4. Multi-objective function based formulation

The MOBPIF calculation of distribution systems for different types of DGs (such as DG-1, DG-2, DG-3 and DG-4) and FACTS controller like SVC size-placement planning with DLMs considers all the previously mentioned indices by strategically giving some weights to each of them. This may be performed since all impact power system performance indices are normalized (values between 0 and 1). The GA based MOBPIF of this kind of problem is given by (35) and (36).

$$MOBPIF = \eta_1 (PLI) + \eta_2 (QLI) + \eta_3 (VDI) + \eta_4 (SCCI) + \eta_5 (EIRI) \quad (35)$$

where

$$\sum_{p=1}^{5}\eta_p = 1 \wedge \eta_p \in (01) \tag{36}$$

The values of $\eta_p$are based on their importance of DPS performance indices in DPSs. The value of $\eta_p$is high when importance of that DPS performance index is of main priority as compared to the others. The values of weighting factors of DPS performance indices are given in Table A10 (Appendix Section) on priority basis. In the present work, the above objective function is optimized by using GA.

These weights of (35) are intended to give the corresponding importance to each impact indices for the penetration of DGs and SVC with DLMs and depend on the required analysis (*e.g.*, planning, operation *etc.*). The weighted normalized indices are used as the components of the objective function due to the fact that, normally, the said indices get their weights by translating their impacts in terms of cost. The cost may either be determined rigorously or through an engineering judgment. Regardless of the fact that one of the particular objectives may get higher satisfaction on the cost of the others, it is desirable if the total cost decreases. However, if harmonious solutions are desired, methods reported in [5–23] may be adopted. Table A10 (refer Appendix Section) shows the values for the weights, as used in present work, considering normal operation analysis and are in line with [4–22]. However, these values may vary according to an engineer's concern. In this analysis, PLI and QLI loss indices receive the first and the second significant weight of 0.40 and 0.30, respectively. The behaviour of voltage profile receives the third significant weight of 0.10 due to its power quality impacts. The SCCI receives the fourth significant weight of 0.10 since it gives important information about the level of currents through the network regarding the maximum thermal capacity of conductors in the distribution systems. The EIRI receives the fifth significant weight of 0.10. This index shows the level of emission of GHG with different types of DGs and SVC.

The multi-objective function (defined in (35)) is minimized subjected to various operational constraints to satisfy the electrical requirements for distribution network. These constraints may be discussed as follows:

(i) *Power flow conservation limits*: the algebraic sum of all the incoming and the outgoing power including line losses over whole distribution network and power generated from DG and FACTS controller like SVC unit should be equal to zero and is stated in (37)

$$P_{SS}(i, V) = \sum_{i=2}^{N_{bus}} P_{Demand}(i, V) + \sum_{n=1}^{N_{TL}} P_{Loss}(V) - P_{WDG\_FACTS\_i} \tag{37}$$

where$N_{TL}$is the number of transmission lines, N_{bus} is the number of buses in the system, $P_{Demand}(i, V)$is the power demand (MW), $P_{Loss}(V)$is the power loss in the system and $P_{WDG\_FACTS\_i}$ is the power delivered to the system by the DGs and the FACTS controller like SVC.

(ii) *Short circuit current capacity or distribution line thermal capacity limits*: power flow through any distribution feeder must comply with the thermal capacity of the line, as given in (38).

$$S_{(i,j)} \le S_{(i,j)\max}. \tag{38}$$

(iii) *Voltage deviation limits*: the voltage drop limits depend on the voltage regulation limits provided by the DISCO and may be given by (39).

$$|V_1 - V_j| \le \Delta V_{\max}. \tag{39}$$

If voltage and MVA limits are satisfied in the system buses for a particular size-location pair, accept that pair for next generation population, else reject the size-placement pair which does not satisfy voltage and MVA limits in the next generation. Obtain the size-placement pair for minimum MOBPIF. All possible generations are tested with operational constraints, the size and the placement corresponding to minimum MOBPIF by the optimum size-placement pair of DGs and FACTS controller like SVC.

5. Simulation results and discussions

The effectiveness of the proposed methodology is tested on IEEE 37-bus distribution test system. The values of system and load data for IEEE 37-bus distribution test system are given in Table A11 of Appendix Section. The details of single-line diagram of IEEE 37-bus distribution system are shown in Fig. 6. The optimization process of GA and the involved physical mechanisms for the calculation of the results are already explained in Section 3. The planning of different types of DGs (such as DG-1, DG-2, DG-3 and DG-4) and FACTS controller like SVC with DLMs (such as CON-INS-RES-COM-REF load models) by GA from minimum total real power loss viewpoint are as follows:

5.1. DG-1 type DG (operating at 1.00 power factor) and SVC

The results for planning of DG-1 type of DG and SVC with DLMs (such as CON-INS-RES-COM-REF load models), as optimized by GA, are featured in Table 1. From Figs. 7–9 and Table 1, the following observations may be made based on DPS performance parameters and indices such as P_{intake}, Q_{intake}, S_{intake}, S_{system}, PL_{min}, QL_{min}, *PLI, QLI, VDI, SCCI, EIRI* and *VP* from minimum total real power loss viewpoint.

(i) *SVC behaves as a generator mode*: the SVC behaves as a generator mode means that reactive power is delivered to the system bus, hence, all the DPS performance parameters and indices are better as compared to DG-1 type DG,
(ii) *SVC behaves as a resonance mode*: the SVC behaves as a resonance mode means that reactive power is neither delivered nor absorbed from the system bus, hence, all the DPS performance parameters and indices are the same as DG-1 type DG,
(iii) *SVC behaves as a load mode*: the SVC behaves as load mode means that reactive power is absorbed from the system bus, hence, all the DPS performance parameters and indices are poor as compared to DG-1 type DG.

Thus, the DPS performance orders would be as follows: DG-1 type DG (operating at 1.00 power factor) and SVC (+0.500) behaves as load mode means that reactive power is absorbed from the system; >DG-1 type DG (operating at 1.00 power factor) and SVC (+0.250) behaves

Table 1
DG (*i.e.* T_1 operating at 1.00 power factor) and SVC planned by GA with DLMs (such as CON-INS-RES-COM-REF) in DPSs from minimum total real power loss viewpoint.

DLMs	WODG_SVC/WDG/WDG + SVC	P_{DG}	Q_{DG}	PF_{DG}	LOC_{DG}	SVC_{alpha}	SVC_{MVAR}	SVC_{LOC}	P_{intake}	Q_{intake}	S_{intake}	S_{system}	P_{Lmin}	Q_{Lmin}	PLI	QLI	VDI	SCCI	EIRI	V_{min}	V_{max}
CON	WODG_SVC	–	–	–	–	–	–	–	3.9039	2.4259	4.5962	4.5962	0.1889	0.1259	100	100	8.13	99.64	100	0.9462	1.03
	WDG-T1-1.00/$SVC_{alpha=115}{}^0$	2.0013	–	1.00	6	–	–	–	1.8081	2.3720	2.9825	4.4935	0.1014	0.0720	53.69	57.18	5.34	99.29	0.6045	0.9749	1.03
	WDG-T1-1.00 + SVC (−0.250)	2.0358	–	1.00	7	115.44	−0.250	6	1.6787	2.3706	2.9048	4.4911	0.0995	0.0706	52.69	56.07	4.92	99.01	0.5634	0.9793	1.03
	WDG-T1-1.00 + SVC (−0.500)	2.2755	–	1.00	6	117.09	−0.500	29	1.3369	2.3699	2.7211	4.4890	0.0974	0.0699	51.58	55.55	4.71	98.25	0.5573	0.9814	1.03
	WDG-T1-1.00 + SVC (+0.250)	1.7987	–	1.00	7	112.25	+0.250	6	2.0408	2.3715	3.1287	4.4958	0.1044	0.0745	55.31	57.76	5.48	99.31	0.6040	0.9714	1.03
	WDG-T1-1.00 + SVC (+0.500)	1.7931	–	1.00	6	110.71	+0.500	29	2.1293	2.3753	3.1902	4.5004	0.1074	0.0755	56.87	59.96	5.76	99.32	0.6039	0.9706	1.03
INS	WODG_SVC	–	–	–	–	–	–	–	3.8709	2.1673	4.4363	4.4363	0.1660	0.1103	100	100	7.59	99.56	100	0.9517	1.03
	WDG-T1-1.00/$SVC_{alpha=115}{}^0$	0.9324	–	1.00	10	–	–	–	2.8898	2.2648	3.6716	4.4228	0.1098	0.0726	66.13	65.86	6.06	99.50	0.7379	0.9805	1.03
	WDG-T1-1.00 + SVC (−0.250)	1.0462	–	1.00	12	115.44	−0.250	6	2.7647	2.2860	3.5874	4.4201	0.1072	0.0711	64.59	64.51	5.93	99.35	0.7178	0.9886	1.03
	WDG-T1-1.00 + SVC (−0.500)	1.1211	–	1.00	13	117.09	−0.500	6	2.6539	2.3160	3.5224	4.4107	0.1001	0.0702	63.06	63.37	5.81	99.15	0.6914	0.9891	1.03
	WDG-T1-1.00 + SVC (+0.250)	0.8267	–	1.00	29	112.25	+0.250	6	3.0104	2.2791	3.7758	4.4235	0.1159	0.0780	69.82	70.68	6.61	99.65	0.7375	0.9715	1.03
	WDG-T1-1.00 + SVC (+0.500)	0.6930	–	1.00	9	110.71	+0.500	6	3.1584	2.2283	3.8653	4.4240	0.1215	0.0803	73.17	72.75	6.63	99.67	0.7373	0.9705	1.03
RES	WODG_SVC	–	–	–	–	–	–	–	3.8304	2.2375	4.4360	4.4360	0.1664	0.1105	100	100	7.58	99.63	100	0.9518	1.03
	WDG-T1-1.00/$SVC_{alpha=115}{}^0$	0.6765	–	1.00	13	–	–	–	3.1377	2.2814	3.8794	4.4242	0.1189	0.0786	71.50	71.13	6.41	99.98	0.8272	0.9812	1.03
	WDG-T1-1.00 + SVC (−0.250)	0.7867	–	1.00	13	115.44	−0.250	6	3.0092	2.2931	3.7833	4.4119	0.1149	0.0761	69.06	68.83	6.26	99.25	0.7865	0.9822	1.03
	WDG-T1-1.00 + SVC (−0.500)	0.9034	–	1.00	15	117.09	−0.500	6	2.8989	2.3089	3.7060	4.4109	0.1146	0.0756	68.89	66.30	6.13	99.15	0.7545	0.9867	1.03
	WDG-T1-1.00 + SVC (+0.250)	0.5763	–	1.00	11	112.25	+0.250	6	3.2369	2.2694	3.9533	4.4345	0.1251	0.0827	75.23	74.83	6.52	99.97	0.8199	0.9767	1.03
	WDG-T1-1.00 + SVC (+0.500)	0.4591	–	1.00	10	110.71	+0.500	6	3.3608	2.2605	4.0546	4.4255	0.1325	0.0874	79.64	79.14	6.67	99.96	0.8177	0.9725	1.03
COM	WODG_SVC	–	–	–	–	–	–	–	3.7987	2.2632	4.4217	4.4217	0.1646	0.1093	100	100	7.52	99.76	100	0.9524	1.03
	WDG-T1-1.00/$SVC_{alpha=115}{}^0$	1.6209	–	1.00	24	–	–	–	2.1933	2.3045	3.1814	4.4165	0.1358	0.0945	82.48	86.42	7.01	97.81	0.9125	0.9577	1.03
	WDG-T1-1.00 + SVC (−0.250)	1.8505	–	1.00	23	115.44	−0.250	30	1.9469	2.2990	3.0127	4.4101	0.1350	0.0935	81.05	85.52	6.93	97.25	0.8825	0.9590	1.03
	WDG-T1-1.00 + SVC (−0.500)	2.0223	–	1.00	24	117.09	−0.500	6	1.7834	2.3216	2.9276	4.4002	0.1340	0.0930	80.88	84.45	6.88	97.05	0.8515	0.9596	1.03
	WDG-T1-1.00 + SVC (+0.250)	1.4613	–	1.00	14	112.25	+0.250	29	2.4134	2.3712	3.3834	4.4182	0.1293	0.0950	82.75	86.88	7.13	98.25	0.9115	0.9567	1.03
	WDG-T1-1.00 + SVC (+0.500)	1.1885	–	1.00	14	110.71	+0.500	31	2.6507	2.3423	3.5373	4.4150	0.1299	0.0952	82.99	86.98	7.15	1.001	0.9111	0.9560	1.03
REF	WODG_SVC	–	–	–	–	–	–	–	3.8369	2.3677	4.5086	4.5086	0.1769	0.1177	100	100	7.83	99.41	100	0.9494	1.03
	WDG-T1-1.00/$SVC_{alpha=115}{}^0$	1.8290	–	1.00	7	–	–	–	1.9881	2.3613	3.0868	4.4884	0.1090	0.0995	57.11	59.04	7.26	99.99	0.6129	0.9771	1.03
	WDG-T1-1.00 + SVC (−0.250)	1.9013	–	1.00	28	115.44	−0.250	6	1.9149	2.3665	3.0443	4.4690	0.1013	0.0980	56.13	57.29	6.06	97.39	0.5881	0.9793	1.03
	WDG-T1-1.00 + SVC (−0.500)	2.0044	–	1.00	28	117.09	−0.500	6	1.7667	2.3706	2.9565	4.4552	0.1012	0.0975	55.24	56.64	5.88	97.25	0.5525	0.9814	1.03
	WDG-T1-1.00 + SVC (+0.250)	1.7428	–	1.00	7	112.25	+0.250	6	2.0149	2.3592	3.1617	4.4885	0.1029	0.0998	57.39	59.66	7.29	99.97	0.6115	0.9712	1.03
	WDG-T1-1.00 + SVC (+0.500)	1.4611	–	1.00	26	110.71	+0.500	31	2.3626	2.3603	3.3396	4.4888	0.1091	0.0999	58.40	60.15	7.31	1.002	0.6110	0.9704	1.03

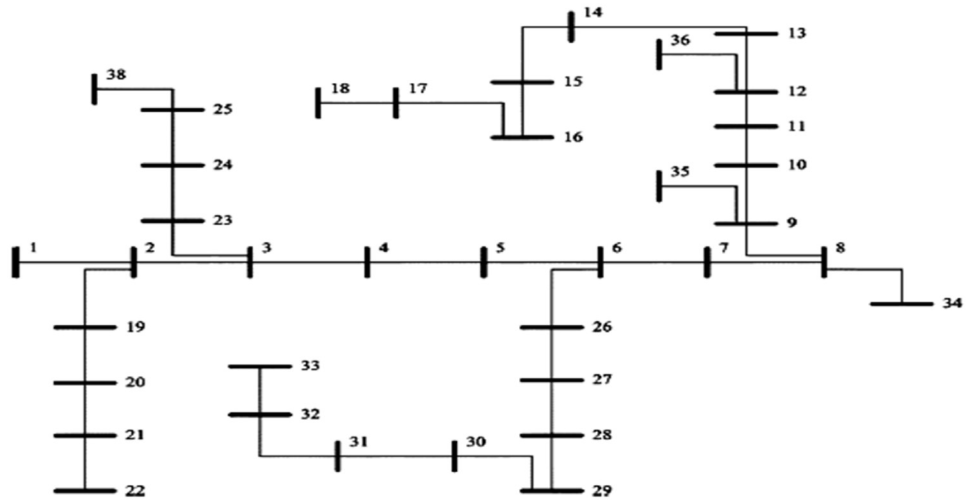

Fig. 6. Single-line diagram of IEEE 37-bus (38-node) distribution test system [5–29].

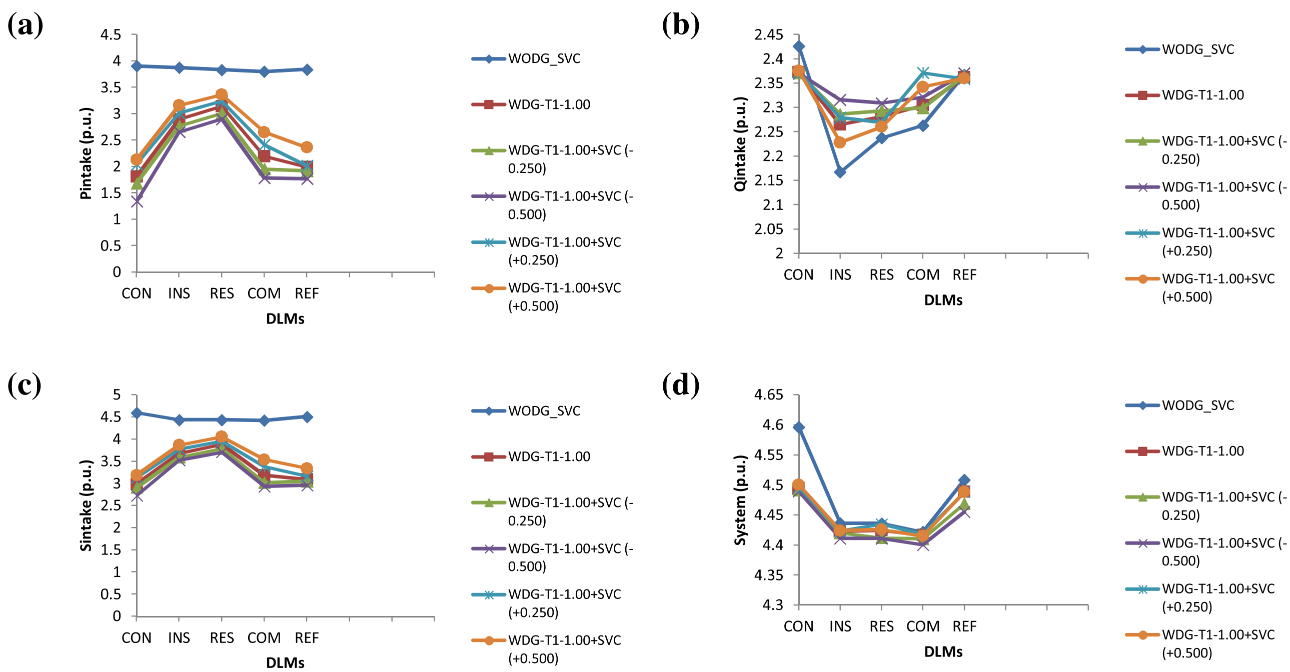

Fig. 7. Pertaining to DG (*i.e.* DG-1 operating at 1.00 power factor) and SVC planned by GA with DLMs (such as CON-INS-RES-COM-REF) in DPSs, profiles of (a) P_{intake}, (b) Q_{intake}, (c) S_{intake} and (d) S_{system}. *T1 means DG-1 type of DG.

as load mode means that reactive power is absorbed from the system; >DG-1 type DG (operating at 1.00 power factor); = DG-1 type DG (operating at 1.00 power factor) and SVC (0.00) behaves as a resonance mode means that reactive power is neither delivered nor absorbed from the system; <DG-1 type DG (operating at 1.00 power factor) and SVC (−0.250) behaves as a generator mode means that reactive power is delivered to the system; <DG-1 type DG (operating at 1.00 power factor) and SVC (−0.500) behaves as a generator mode means that reactive power is delivered to the system.

5.2. DG-2 type DG (operating at 0.80 leading power factor) and SVC

The GA optimized results for planning of DG-2 type DG (operating at 0.80 leading power factor) and SVC with DLMs (such as CON-INS-RES-COM-REF load models) are featured in Table 2. Figs. 10–12 and Table 2 help to note the following observations based on the DPS performance parameters and indices such as P_{intake}, Q_{intake}, S_{intake}, S_{system}, PL_{min}, QL_{min}, *PLI, QLI, VDI, SCCI, EIRI* and *VP* from minimum total real power loss viewpoint.

(i) *SVC behaves as a generator mode*: the SVC behaves as a generator mode means that reactive power is delivered to the system bus, hence, all the DPS performance parameters and indices are better as compared to DG-2 type DG (operating at 0.80 leading power factor),

Table 2
DG (*i.e.* T_2 operating at 0.80 leading power factor) and SVC planned by GA with DLMs (such as CON-INS-RES-COM-REF) in DPSs from minimum total real power loss viewpoint.

DLMs	WODG_SVC/WDG/WDG + SVC	P_{DG}	Q_{DG}	PF_{DG}	LOC_{DG}	SVC_{alpha}	SVC_{MVAR}	SVC_{LOC}	P_{intake}	Q_{intake}	S_{intake}	S_{ystem}	P_{Lmin}	Q_{Lmin}	PLI	QLI	VDI	SCCI	EIRI	V_{min}	V_{max}
CON	WODG_SVC	–	–	–	–	–	–	–	3.9039	2.4259	4.5962	4.5962	0.1889	0.1259	100	100	8.13	99.64	100	0.9462	1.03
	WDG-T2-0.80ld/$SVC_{alpha=115}{}^0$	1.3658	1.0243	0.80	6	–	–	–	2.4315	1.3351	2.7739	4.4707	0.0823	0.0595	43.58	47.29	5.29	99.29	0.9679	0.9749	1.03
	WDG-T2-0.80ld + SVC (−0.250)	1.3888	1.0416	0.80	6	115.44	−0.250	30	2.4074	1.3172	2.7442	4.4595	0.0812	0.0589	43.03	46.79	5.25	99.28	0.9660	0.9793	1.03
	WDG-T2-0.80ld + SVC (−0.500)	1.6911	1.2683	0.80	26	117.09	−0.500	30	2.0919	1.0827	2.3555	4.4541	0.0681	0.0511	36.05	40.57	4.64	99.27	0.9567	0.9814	1.03
	WDG-T2-0.80ld + SVC (+0.250)	1.2356	0.9267	0.80	6	112.25	+0.250	6	2.5680	1.4367	2.9426	4.4781	0.0886	0.0634	46.94	50.37	5.56	99.30	0.9800	0.9714	1.03
	WDG-T2-0.80ld + SVC (+0.500)	1.0209	0.7657	0.80	6	110.71	+0.500	6	2.7948	1.6052	3.2230	4.4924	0.1008	0.0709	53.36	56.30	5.99	99.32	0.9685	0.9706	1.03
INS	WODG_SVC	–	–	–		–	–	–	3.8709	2.1973	4.4363	4.4563	0.1660	0.1103	100	100	7.59	99.56	100	0.9517	1.03
	WDG-T2-0.80ld/$SVC_{alpha=115}{}^0$	0.6592	0.4944	0.80	30	–	–	–	3.1494	1.8182	3.6365	4.4557	0.0958	0.0643	57.71	58.34	6.42	99.98	0.9007	0.9805	1.03
	WDG-T2-0.80ld + SVC (−0.250)	0.7909	0.5932	0.80	30	115.44	−0.250	6	3.0100	1.6530	3.4233	4.4531	0.0867	0.0586	52.24	53.15	6.19	99.27	0.9000	0.9886	1.03
	WDG-T2-0.80ld + SVC (−0.500)	0.8115	0.6139	0.80	13	117.09	−0.500	30	2.6919	1.7039	3.1431	4.4400	0.0815	0.0534	50.45	51.47	5.75	99.12	0.8997	0.9891	1.03
	WDG-T2-0.80ld + SVC (+0.250)	0.5248	0.3936	0.80	29	112.25	+0.250	6	3.2952	1.8777	3.7926	4.4559	0.1090	0.0724	57.91	59.32	6.68	99.98	0.9010	0.9715	1.03
	WDG-T2-0.80ld + SVC (+0.500)	0.4684	0.3513	0.80	28	110.71	+0.500	6	3.3895	1.8941	3.8666	4.4564	0.1115	0.0794	59.27	61.45	6.90	99.99	0.9015	0.9705	1.03
RES	WODG_SVC	–	–	–	–	–	–	–	3.8304	2.2475	4.4860	4.4563	0.1664	0.1105	100	100	7.58	99.63	100	0.9518	1.03
	WDG-T2-0.80ld/$SVC_{alpha=115}{}^0$	0.4405	0.3304	0.80	31	–	–	–	3.3654	1.9656	3.8974	4.4557	0.1131	0.0751	68.11	67.98	6.79	99.95	0.9030	0.9812	1.03
	WDG-T2-0.80ld + SVC (−0.250)	0.6288	0.4716	0.80	31	115.44	−0.250	6	3.1732	1.8247	3.6155	4.4531	0.0976	0.0653	58.70	59.06	6.46	98.90	0.8905	0.9822	1.03
	WDG-T2-0.80ld + SVC (−0.500)	0.8124	0.6393	0.80	24	117.09	−0.500	6	3.0072	1.6594	3.4346	4.4400	0.0915	0.0616	55.60	56.87	6.15	96.96	0.9000	0.9867	1.03
	WDG-T2-0.80ld + SVC (+0.250)	0.2538	0.1903	0.80	31	112.25	+0.250	6	3.5797	2.0987	4.3222	4.4559	0.1145	0.0768	68.35	68.19	7.12	99.98	0.9032	0.9767	1.03
	WDG-T2-0.80ld + SVC (+0.500)	0.2412	0.1809	0.80	29	110.71	+0.500	6	3.5739	2.0931	4.1867	4.4564	0.1177	0.0788	69.17	70.30	7.19	99.99	0.9035	0.9725	1.03
COM	WODG_SVC	–	–	–	–	–	–	–	3.8987	2.2932	4.4517	4.4517	0.1646	0.1093	100	100	7.52	99.76	100	0.9524	1.03
	WDG-T2-0.80ld/$SVC_{alpha=115}{}^0$	1.6563	1.2422	0.80	23	–	–	–	2.1509	1.0645	2.3999	4.4515	0.1252	0.0896	76.07	82.05	6.79	98.45	0.9021	0.9577	1.03
	WDG-T2-0.80ld + SVC (−0.250)	1.7098	1.2823	0.80	24	115.44	−0.250	6	2.0190	1.0483	2.2641	4.4511	0.1217	0.0850	72.15	79.13	6.56	97.15	0.9015	0.9590	1.03
	WDG-T2-0.80ld + SVC (−0.500)	1.8000	1.3500	0.80	24	117.09	−0.500	30	2.0130	0.9360	2.1595	4.4501	0.1201	0.0815	70.24	75.16	6.17	96.25	0.9001	0.9596	1.03
	WDG-T2-0.80ld + SVC (+0.250)	1.5468	1.601	0.80	31	112.25	+0.250	29	2.3119	1.2257	2.6150	4.4525	0.1258	0.0905	77.19	83.15	6.89	98.48	0.9024	0.9567	1.03
	WDG-T2-0.80ld + SVC (+0.500)	1.5244	1.1433	0.80	31	110.71	+0.500	27	2.2319	1.3181	2.6285	4.4559	0.1266	0.050	78.20	84.16	6.96	99.25	0.9026	0.9560	1.03
REF	WODG_SVC	–	–	–	–	–	–	–	3.8369	2.3677	4.5086	4.5086	0.1769	0.1177	100	100	7.83	99.41	100	0.9494	1.03
	WDG-T2-0.80ld/$SVC_{alpha=115}{}^0$	1.3080	0.9810	0.80	26	–	–	–	2.4916	1.3727	2.8447	4.4697	0.0808	0.0586	45.70	49.78	5.31	99.90	0.9472	0.9771	1.03
	WDG-T2-0.80ld + SVC (−0.250)	1.3996	1.0497	0.80	27	115.44	−0.250	30	2.3006	1.1068	2.6332	4.4516	0.0748	0.0552	42.32	46.88	5.14	98.67	0.9401	0.9793	1.03
	WDG-T2-0.80ld + SVC (−0.500)	1.5130	1.1347	0.80	7	117.09	−0.500	30	2.2722	1.2192	2.5463	4.4506	0.0738	0.0515	41.76	43.75	4.62	97.24	0.9378	0.9814	1.03
	WDG-T2-0.80ld + SVC (+0.250)	1.1610	0.8707	0.80	26	112.25	+0.250	6	2.6390	1.4861	3.0677	4.4698	0.0876	0.0627	49.53	53.26	5.59	99.95	0.9486	0.9712	1.03
	WDG-T2-0.80ld + SVC (+0.500)	1.0404	0.7803	0.80	6	110.71	+0.500	6	2.7611	1.5817	3.1871	4.4699	0.0960	0.0676	54.31	57.47	5.81	99.98	0.9498	0.9704	1.03

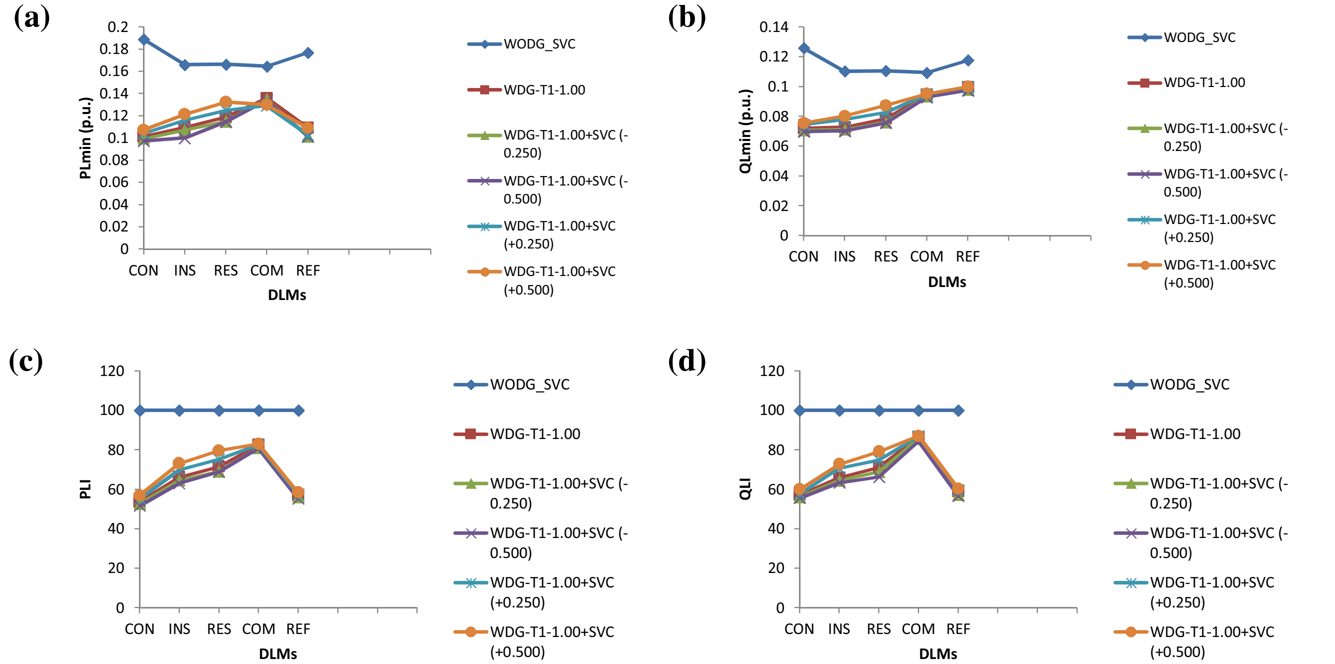

Fig. 8. Pertaining to DG (*i.e.* DG-1 operating at 1.00 power factor) and SVC planned by GA with DLMs (such as CON-INS-RES-COM-REF) in DPSs, profiles of (a) P_{Lmin}, (b) Q_{Lmin}, (c) *PLI* and (d) *QLI*. *T1 means DG-1 type of DG.

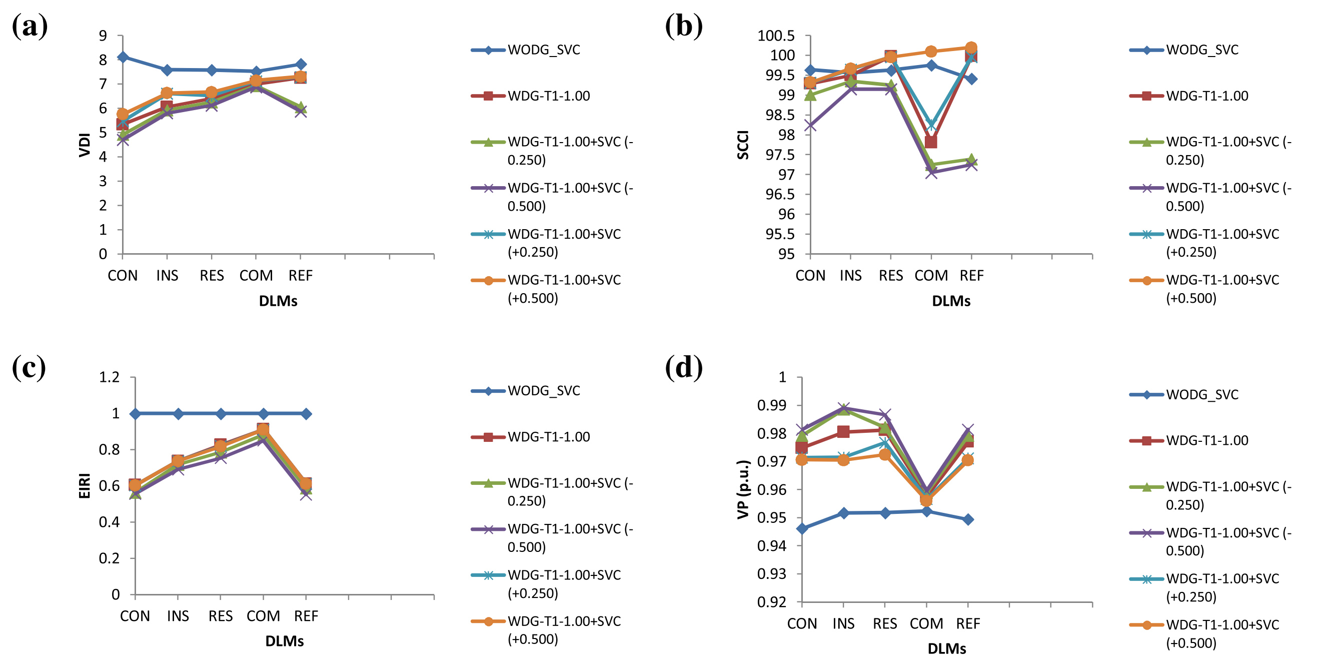

Fig. 9. Pertaining to DG (*i.e.* DG-1 operating at 1.00 power factor) and SVC planned by GA with DLMs (such as CON-INS-RES-COM-REF) in DPSs, profiles of (a) *VDI*, (b) *SCCI*, (c) *EIRI* and (d) *VP*. *T1 means DG-1 type of DG.

(ii) *SVC behaves as a resonance mode*: the SVC behaves as a resonance mode means that reactive power is neither delivered nor absorbed from the system bus, hence, all the DPS performance parameters and indices are same as DG-2 type DG (operating at 0.80 leading power factor),

(iii) *SVC behaves as a load mode*: the SVC behaves as a load mode means that reactive power is absorbed from the system bus, hence, all the DPS performance parameters and indices are poor as compared to DG-2 type DG (operating at 0.80 leading power factor).

Thus, the DPS performance orders would be as follows: DG-2 type DG (operating at 0.80 leading power factor) and SVC (+0.500) behaves as a load mode means that reactive power is absorbed from the system; >DG-2 type DG (operating at 0.80 leading power factor) and SVC (+0.250) behaves as a load mode means that reactive power is absorbed from the system; >DG-2 type DG (operating at 0.80 leading power factor); = DG-2 type DG (operating at 0.80 leading power factor) and SVC (0.00) behaves as a resonance mode means that reactive power is neither delivered nor absorbed from the system; <DG-2 type DG (operating at 0.80 leading power factor) and SVC (−0.250) behaves as

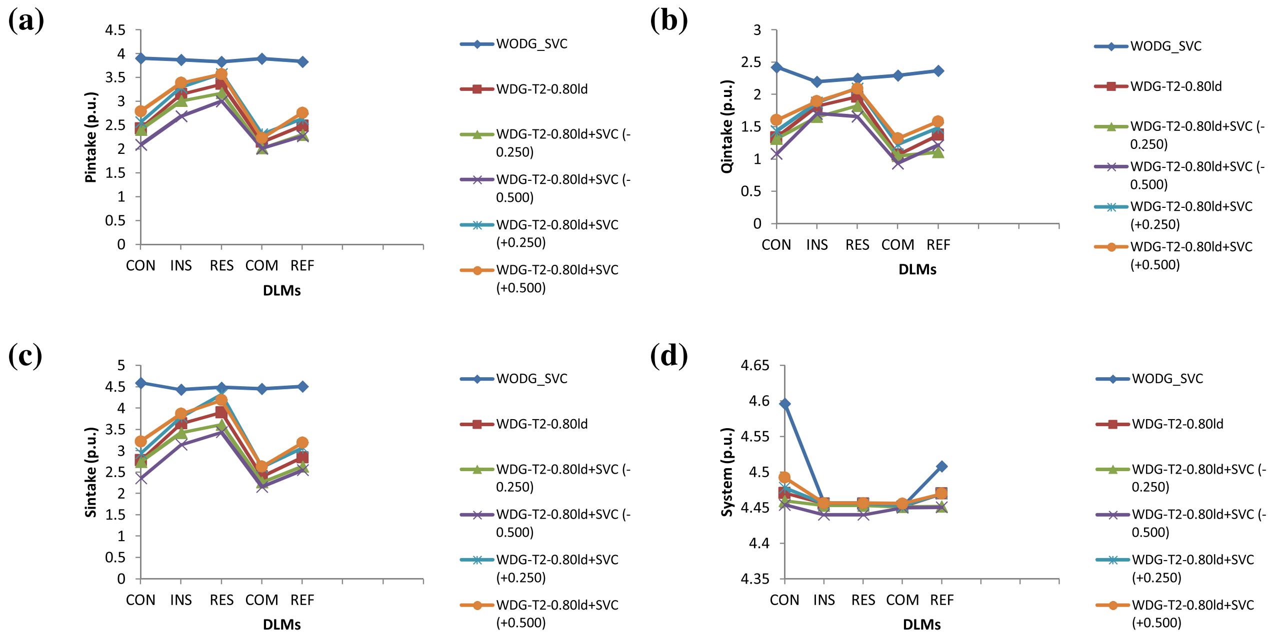

Fig. 10. Pertaining to DG (*i.e.* DG-2 operating at 0.80 leading power factor) and SVC planned by GA with DLMs (such as CON-INS-RES-COM-REF) in DPSs, profiles of (a) P_{intake}, (b) Q_{intake}, (c) S_{intake} and (d) S_{system}. *'ld' means leading operating power factor of DG; T2 means DG-2 type of DG.

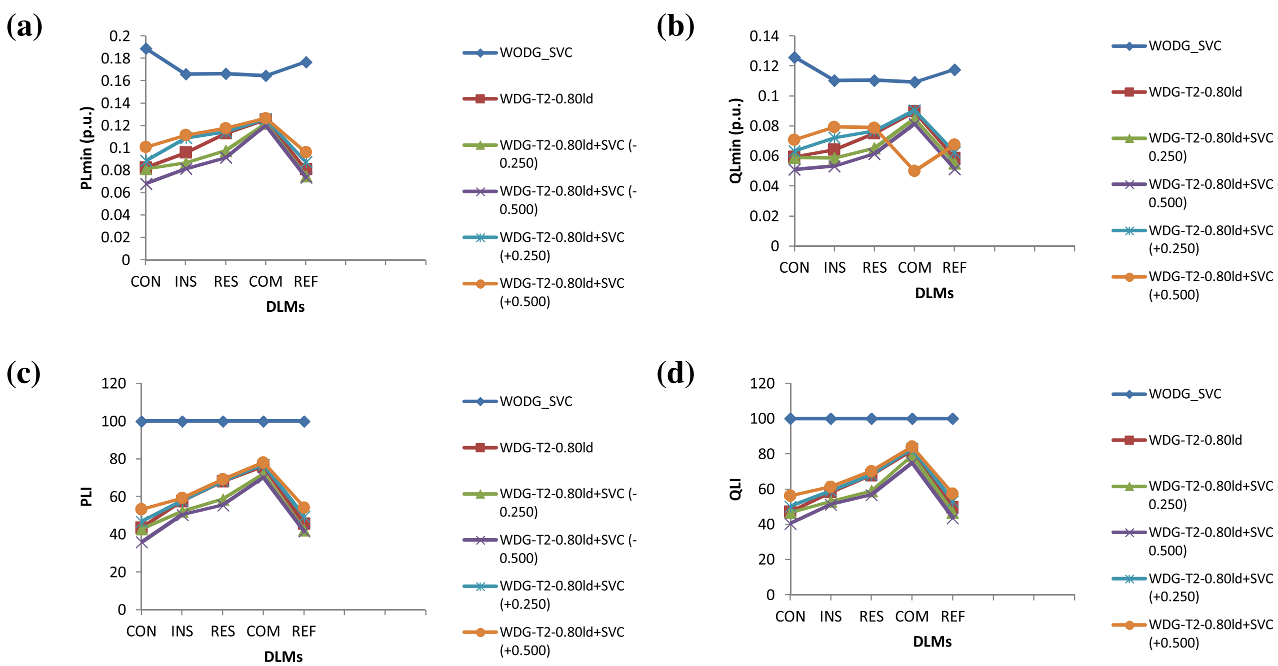

Fig. 11. Pertaining to DG (*i.e.* DG-2 operating at 0.80 leading power factor) and SVC planned by GA with DLMs (such as CON-INS-RES-COM-REF) in DPSs, profiles of (a) P_{Lmin}, (b) Q_{Lmin}, (c) *PLI* and (d) *QLI*. *'ld' means leading operating power factor of DG; T2 means DG-2 type of DG.

a generator mode means that reactive power is delivered to the system; <DG-2 type DG (operating at 0.80 leading power factor) and SVC (−0.500) behaves as a generator mode means that reactive power is delivered to the system.

5.3. DG-3 type DG (operating at 0.00 power factor) and SVC

Table 3 presents the GA optimized results for planning of DG-3 type DG (operating at 0.00 power factor) and SVC with DLMs (such as CON-INS-RES-COM-REF load models). Based on the DPS performance parameters and indices the following points may be stated (refer Figs. 13–15 and Table 3).

(i) *SVC behaves as a generator mode*: the SVC behaves as a generator mode means that reactive power is delivered to the system bus hence the all the DPS performance parameters and indices are better as compared to DG-3 type DG (operating at 0.00 power factor),

Table 3
DG (*i.e.* T_3 operating at 0.00 power factor) and SVC planned by GA with DLMs (such as CON-INS-RES-COM-REF) in DPSs from minimum total real power loss viewpoint.

DLMs	WODG_SVC/WDG/WDG + SVC	P_{DG}	Q_{DG}	PF_{DG}	LOC_{DG}	SVC_{alpha}	SVC_{MVAR}	SVC_{LOC}	P_{intake}	Q_{intake}	S_{intake}	S_{ystem}	P_{Lmin}	Q_{Lmin}	PLI	QLI	VDI	SCCI	EIRI	V_{min}	V_{max}
CON	WODG_SVC	0.00	–	–	–	–	–	–	3.9039	2.4259	4.5962	4.5962	0.1889	0.1259	100	100	8.13	99.64	100	0.9462	1.03
	WDG-T3-0.00/$SVC_{alpha=115}{}^0$	0.00	1.2176	0.00	30	–	–	–	3.8492	1.7723	4.1642	4.5308	0.1342	0.0899	71.04	71.44	6.99	99.31	0.4832	0.9749	1.03
	WDG-T3-0.00 + SVC (−0.250)	0.00	1.3606	0.00	30	115.44	−0.250	6	3.8195	1.0299	3.9349	4.5214	0.1245	0.0805	61.42	67.85	6.87	99.28	0.4528	0.9793	1.03
	WDG-T3-0.00 + SVC (−0.500)	0.00	1.5322	0.00	30	117.09	−0.500	6	3.8017	0.8601	3.9166	4.5142	0.1167	0.0723	60.39	65.31	6.73	99.25	0.4201	0.9814	1.03
	WDG-T3-0.00 + SVC (+0.250)	0.00	0.9895	0.00	30	112.25	+0.250	6	3.8514	1.4016	4.0985	4.5310	0.1364	0.0911	72.23	72.34	7.19	99.32	0.4844	0.9715	1.03
	WDG-T3-0.00 + SVC (+0.500)	0.00	0.8813	0.00	6	110.71	+0.500	6	3.8105	1.5236	4.1296	4.5320	0.1375	0.1049	73.31	73.34	7.32	99.33	0.4860	0.9706	1.03
INS	WODG_SVC	0.00		–		–	–		3.8709	2.1673	4.4363	4.4863	0.1660	0.1103	100	100	7.59	99.86	100	0.9527	1.03
	WDG-T3-0.00/$SVC_{alpha=115}{}^0$	0.00	1.1058	0.00	30	–	–		3.8422	1.1792	4.0191	4.4703	0.1315	0.0880	79.23	79.77	6.76	99.81	0.7144	0.9805	1.03
	WDG-T3-0.00 + SVC (−0.250)	0.00	1.2715	0.00	30	115.44	−0.250	6	3.8136	1.0351	3.9305	4.4426	0.1222	0.0787	69.62	70.39	6.64	99.80	0.6701	0.9876	1.03
	WDG-T3-0.00 + SVC (−0.500)	0.00	1.4058	0.00	30	117.09	−0.500	6	3.8058	0.9190	3.9041	4.4139	0.1137	0.0600	66.57	65.55	6.55	98.78	0.5589	0.9891	1.03
	WDG-T3-0.00 + SVC (+0.250)	0.00	0.9551	0.00	31	112.25	+0.250	6	3.8064	1.3194	4.0604	4.4725	0.1325	0.0919	80.01	83.32	6.83	99.82	0.7155	0.9740	1.03
	WDG-T3-0.00 + SVC (+0.500)	0.00	0.5240	0.00	6	110.71	+0.500	6	3.8506	1.6696	4.2005	4.4735	0.1365	0.1003	81.27	85.92	7.17	99.83	0.7157	0.9710	1.03
RES	WODG_SVC	0.00	–	–	–	–	–		3.8304	2.2375	4.4360	4.4760	0.1664	0.1105	100	100	7.58	99.93	100	0.9518	1.03
	WDG-T3-0.00/$SVC_{alpha=115}{}^0$	0.00	1.0971	0.00	30	–	–		3.8220	1.2156	4.0107	4.4673	0.1291	0.0862	77.61	78.04	6.75	99.91	0.5416	0.9812	1.03
	WDG-T3-0.00 + SVC (−0.250)	0.00	1.2748	0.00	30	115.44	−0.250	6	3.8070	1.0543	3.9096	4.4501	0.1197	0.0770	67.98	75.69	6.62	98.85	0.5201	0.9822	1.03
	WDG-T3-0.00 + SVC (−0.500)	0.00	1.2852	0.00	30	117.09	−0.500	6	3.8074	1.0449	3.9074	4.4409	0.1108	0.0670	65.04	73.74	5.42	97.95	0.5176	0.9867	1.03
	WDG-T3-0.00 + SVC (+0.250)	0.00	0.9694	0.00	30	112.25	+0.250	31	3.8295	1.3322	4.4251	4.4694	0.1298	0.0865	78.01	78.25	6.84	99.91	0.5419	0.9767	1.03
	WDG-T3-0.00 + SVC (+0.500)	0.00	0.6983	0.00	26	110.71	+0.500	6	3.3312	1.5616	4.1380	4.4697	0.1342	0.0970	80.72	80.75	7.03	99.92	0.5421	0.9725	1.03
COM	WODG_SVC	0.00	–	–	–	–	–		3.7986	2.2632	4.4217	4.4417	0.1646	0.1093	100	100	7.52	99.96	100	0.9524	1.03
	WDG-T3-0.00/$SVC_{alpha=115}{}^0$	0.00	0.7391	0.00	30	–	–		3.7969	1.5594	4.1047	4.4385	0.1312	0.0871	79.73	79.72	6.96	98.89	0.6890	0.9577	1.03
	WDG-T3-0.00 + SVC (−0.250)	0.00	0.7419	0.00	30	115.44	−0.250	31	3.6970	1.5568	4.0038	4.4286	0.1211	0.0770	69.69	74.67	5.96	96.99	0.6580	0.9590	1.03
	WDG-T3-0.00 + SVC (−0.500)	0.00	0.9336	0.00	14	117.09	−0.500	30	3.8163	1.3839	4.0083	4.4119	0.1157	0.0659	65.64	72.96	5.53	95.89	0.6265	0.9596	1.03
	WDG-T3-0.00 + SVC (+0.250)	0.00	0.6006	0.00	30	112.25	+0.250	6	3.7958	1.6897	4.1549	4.4365	0.1349	0.0874	80.95	80.85	7.06	98.95	0.6893	0.9567	1.03
	WDG-T3-0.00 + SVC (+0.500)	0.00	0.6717	0.00	30	110.71	+0.500	6	3.7978	1.6227	4.1289	4.4374	0.1388	0.0881	81.70	81.67	7.10	98.97	0.6895	0.9560	1.03
REF	WODG_SVC	0.00	–	–	–	–	–		3.8369	2.3677	4.5086	4.5086	0.1769	0.1177	100	100	7.83	99.61	100	0.9494	1.03
	WDG-T3-0.00/$SVC_{alpha=115}{}^0$	0.00	1.1768	0.00	30	–	–		3.9230	1.1908	4.5041	4.5041	0.1300	0.0870	73.49	73.90	6.84	98.59	0.5030	0.9771	1.03
	WDG-T3-0.00 + SVC (−0.250)	0.00	1.3408	0.00	30	115.44	−0.250	6	3.2280	1.0316	3.2645	4.4935	0.1207	0.0778	71.90	64.62	6.71	97.62	0.4801	0.9793	1.03
	WDG-T3-0.00 + SVC (−0.500)	0.00	1.4604	0.00	30	117.09	−0.500	31	3.0330	0.9076	3.0390	4.3902	0.1124	0.0692	69.89	60.83	5.61	96.64	0.4587	0.9814	1.03
	WDG-T3-0.00 + SVC (+0.250)	0.00	1.0510	0.00	30	112.25	+0.250	6	3.9202	1.3137	4.2398	4.5129	0.1306	0.0872	74.84	74.06	6.94	98.57	0.5033	0.9712	1.03
	WDG-T3-0.00 + SVC (+0.500)	0.00	0.8164	0.00	30	110.71	+0.500	6	3.9177	1.5447	4.5184	4.5189	0.1314	0.0894	75.99	76.00	7.13	98.59	0.5037	0.9704	1.03

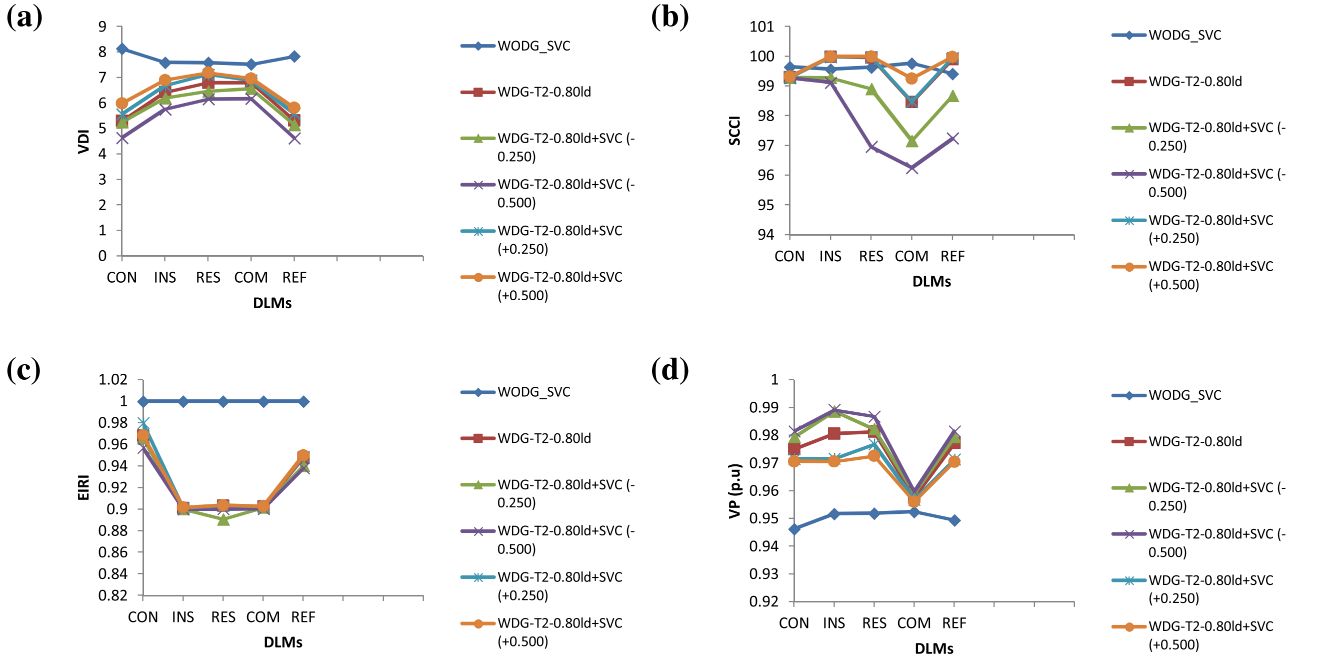

Fig. 12. Pertaining to DG (*i.e.* DG-2 operating at 0.80 leading power factor) and SVC planned by GA with DLMs (such as CON-INS-RES-COM-REF) in DPSs, profiles of (a) *VDI*, (b) *SCCI*, (c) *EIRI* and (d) *VP*. *'ld' means leading operating power factor of DG; T2 means DG-2 type of DG.

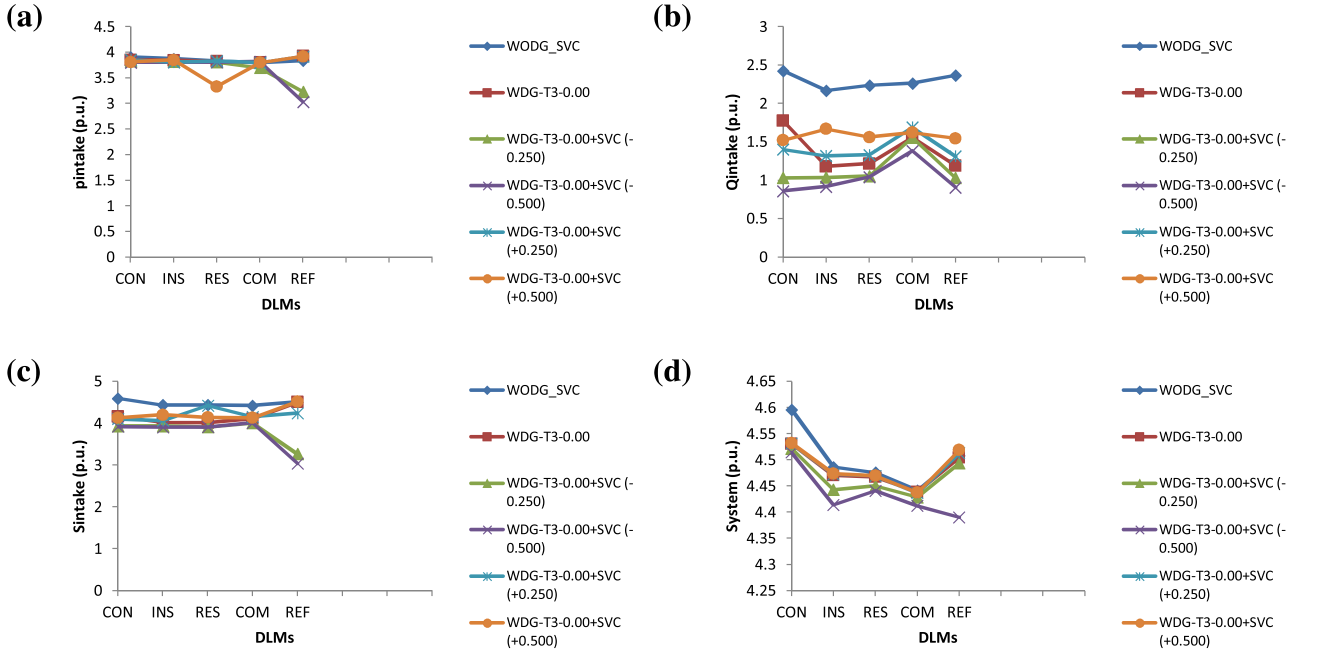

Fig. 13. Pertaining to DG (*i.e.* DG-3 operating at 0.00 power factor) and SVC planned by GA with DLMs (such as CON-INS-RES-COM-REF) in DPSs, profiles of (a) P_{intake}, (b) Q_{intake}, (c) S_{intake} and (d) S_{system}. *T3 means DG-3 type of DG.

(ii) *SVC behaves as a resonance mode*: the SVC behaves as a resonance mode means that reactive power is neither delivered nor absorbed from the system bus, hence, all the DPS performance parameters and indices are same as DG-4 type DG (operating at 0.00 power factor) and

(iii) *SVC behaves as a load mode*: the SVC behaves as a load mode means that reactive power is absorbed from the system bus, hence, all the DPS performance parameters and indices are poor as compared to DG-3 type DG (operating at 0.00 power factor).

Thus, the DPS performance orders would be as follows: DG-3 type DG (operating at 0.00 power factor) and SVC (+0.500) behaves as load mode means that reactive power absorbed from the system; >DG-3 type DG (operating at 0.00 power factor) and SVC (+0.250) behaves as load mode means that reactive power absorbed from the system; > DG-3 type DG (operating at 0.00 power factor); = DG-3 type DG (operating at 0.00 power factor) and SVC (0.00) behaves as a resonance mode means that reactive power is neither delivered nor absorbed from the system; <DG-3 type DG (operating at 0.00 power factor) and SVC (−0.250) behaves as a generator mode means that reactive

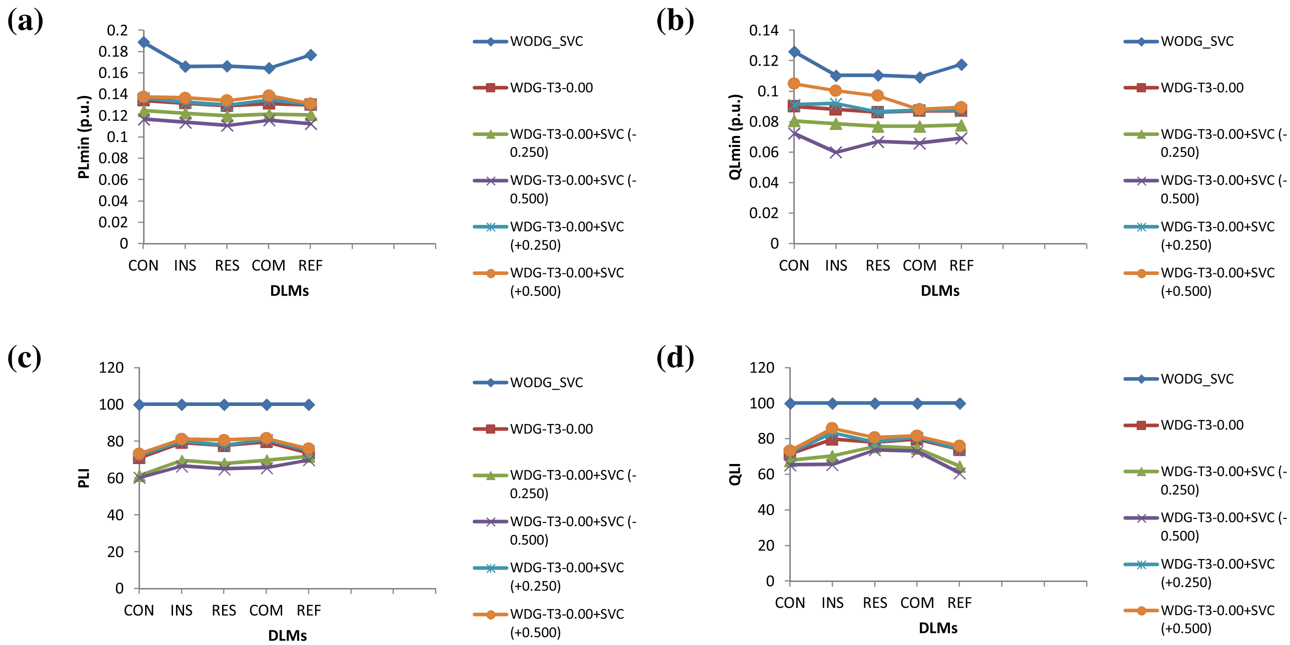

Fig. 14. Pertaining to DG (*i.e.* DG-3 operating at 0.00 power factor) and SVC planned by GA with DLMs (such as CON-INS-RES-COM-REF) in DPSs, profiles of (a) P_{Lmin}, (b) Q_{Lmin}, (c) *PLI* and (d) *QLI*. *T3 means DG-3 type of DG.

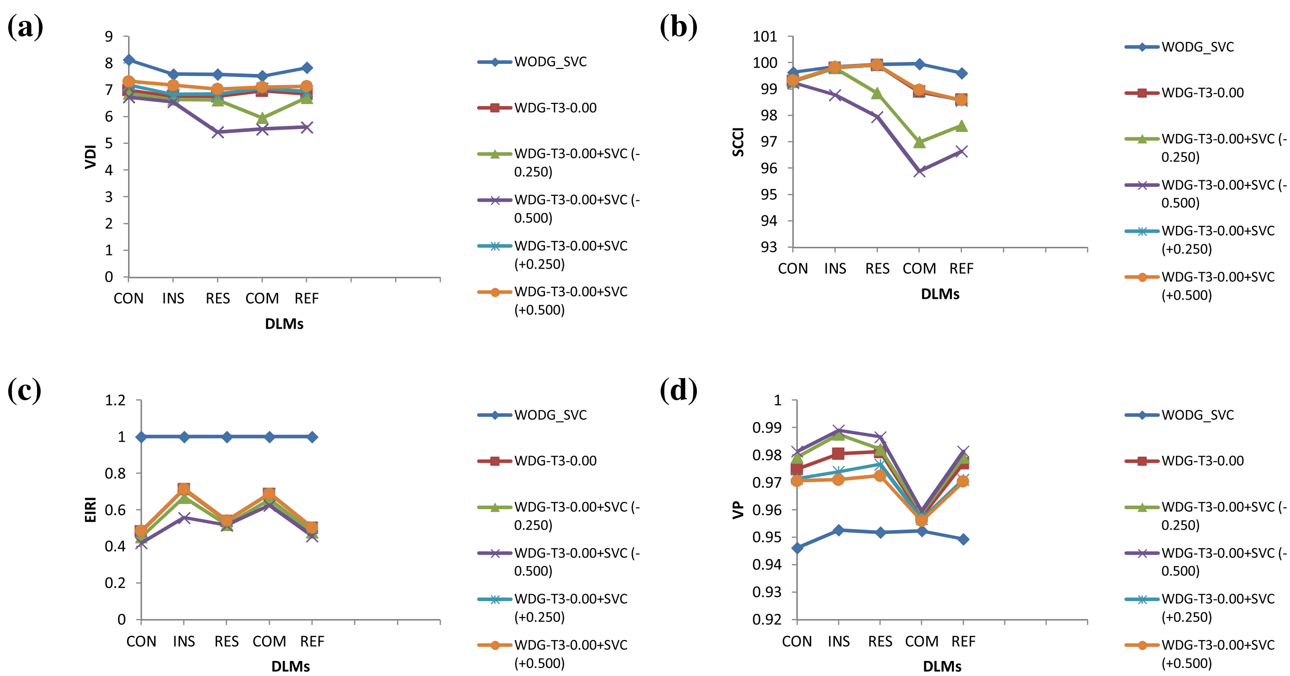

Fig. 15. Pertaining to DG (*i.e.* DG-3 operating at 0.00 power factor) and SVC planned by GA with DLMs (such as CON-INS-RES-COM-REF) in DPSs, profiles of (a) *VDI*, (b) *SCCI*, (c) *EIRI* and (d) *VP*. *T3 means DG-3 type of DG.

power is delivered to the system; <DG-3 type DG (operating at 0.00 power factor) and SVC (−0.500) behaves as a generator mode means that reactive power is delivered to the system.

5.4. DG-4 type DG (operating at 0.80 lagging power factor) and SVC

The results for planning of DG-4 type DG (operating at 0.80 lagging power factor) and SVC with DLMs (such as CON-INS-RES-COM-REF load models) are featured in Table 4. From this table the following points may be noted (also refer Figs. 16–18).

(i) *SVC behaves as a generator mode*: the SVC behaves as a generator mode means that reactive power is delivered to the system bus, hence, all the DPS performance parameters and indices are better as compared to DG-4 type DG (operating at 0.80 lagging power factor),

Table 4
DG (*i.e.* T_4 operating at 0.80 lagging power factor) and SVC planned by GA with DLMs (such as CON-INS-RES-COM-REF) in DPSs from minimum total real power loss viewpoint.

DLMs	WODG_SVC/WDG/WDG + SVC	P_{DG}	Q_{DG}	PF_{DG}	LOC_{DG}	SVC_{alpha}	SVC_{MVAR}	SVC_{LOC}	P_{intake}	Q_{intake}	S_{intake}	S_{system}	P_{Lmin}	Q_{Lmin}	PLI	QLI	VDI	SCCI	EIRI	V_{min}	V_{max}
CON	WODG_SVC	–	–	–	–	–	–	–	3.9039	2.4259	4.5962	4.5962	0.1889	0.1259	100	100	8.13	99.64	100	0.9462	1.03
	WDG-T4-0.80lg/$SVC_{alpha=115}{}^0$	1.3658	−1.0243	0.80	6	–	–	–	2.5302	3.4462	4.2753	4.5684	0.1710	0.1119	95.83	98.78	7.16	98.31	0.7514	0.9759	1.03
	WDG-T4-0.80lg + SVC (−0.250)	1.4652	−1.0989	0.80	7	115.44	−0.250	31	2.4389	3.5391	4.2749	4.5542	0.1655	0.1015	93.75	92.65	6.10	95.25	0.6314	0.9813	1.03
	WDG-T4-0.80lg + SVC (−0.500)	1.6908	−1.2681	0.80	6	117.09	−0.500	30	2.0151	3.6967	4.1095	4.4560	0.1585	0.0985	91.55	90.58	5.01	93.46	0.5019	0.9864	1.03
	WDG-T4-0.80lg + SVC (+0.250)	1.2356	−0.9267	0.80	6	112.25	+0.250	27	2.6597	3.3467	4.2786	4.5876	0.1755	0.1210	96.09	99.09	7.25	98.35	0.8125	0.9714	1.03
	WDG-T4-0.80lg + SVC (+0.500)	1.1048	−0.8286	0.80	6	110.71	+0.500	27	2.7864	3.2472	4.2789	4.5877	0.1862	0.1225	96.21	99.21	7.36	98.45	0.8240	0.9706	1.03
INS	WODG_SVC	–	–	–		–	–		3.8709	2.1673	4.4363	4.4463	0.1660	0.1203	100	100	7.59	99.56	100	0.9517	1.03
	WDG-T4-0.80lg/$SVC_{alpha=115}{}^0$	0.6592	−0.4944	0.80	30	–	–		3.8709	2.1673	4.4363	4.4455	0.1560	0.1003	97.14	98.45	6.59	97.56	0.7995	0.9805	1.03
	WDG-T4-0.80lg + SVC (−0.250)	0.7909	−0.5932	0.80	30	115.44	−0.250	6	3.8695	2.1612	4.4259	4.4255	0.1445	0.0995	95.01	92.23	5.45	95.23	0.6575	0.9906	1.03
	WDG-T4-0.80lg + SVC (−0.500)	1.0433	−0.7825	0.80	6	117.09	−0.500	31	3.7589	2.1548	4.356	4.3640	0.1395	0.0885	90.25	89.56	5.12	92.56	0.5432	0.9991	1.03
	WDG-T4-0.80lg + SVC (+0.250)	0.5248	−0.3936	0.80	29	112.25	+0.250	6	3.8805	2.1683	4.4456	4.4360	0.1635	0.1121	97.23	99.25	7.36	98.78	0.8008	0.9815	1.03
	WDG-T4-0.80lg + SVC (+0.500)	0.4206	−0.3154	0.80	28	110.71	+0.500	6	3.8865	2.1783	4.4850	4.4361	0.1640	0.1201	97.95	99.59	7.45	98.89	0.8129	0.9805	1.03
RES	WODG_SVC	–	–	–	–	–	–		3.8304	2.2375	4.4360	4.4660	0.1664	0.1105	100	100	7.58	99.63	100	0.9518	1.03
	WDG-T4-0.80lg/$SVC_{alpha=115}{}^0$	0.4405	−0.3304	0.80	31	–	–		3.3929	2.5932	4.2704	4.4615	0.1606	0.1076	96.52	97.40	6.32	97.54	0.8730	0.9812	1.03
	WDG-T4-0.80lg + SVC (−0.250)	0.6015	−0.4511	0.80	30	115.44	−0.250	6	3.3856	2.5912	4.2609	4.4501	0.1595	0.0925	90.12	94.01	5.21	95.89	0.7589	0.9892	1.03
	WDG-T4-0.80lg + SVC (−0.500)	0.8044	−0.6033	0.80	6	117.09	−0.500	27	3.2569	2.5254	4.1564	4.3895	0.1423	0.0826	89.89	90.36	5.01	93.56	0.6434	0.9967	1.03
	WDG-T4-0.80lg + SVC (+0.250)	0.2538	−0.1903	0.80	31	112.25	+0.250	6	3.3989	2.5986	4.2789	4.4525	0.1610	0.1089	96.89	98.86	7.24	98.81	0.8833	0.9807	1.03
	WDG-T4-0.80lg + SVC (+0.500)	0.2450	−0.1837	0.80	30	110.71	+0.500	6	3.3563	2.5236	4.2258	4.4535	0.1645	0.1101	96.99	98.89	7.33	98.97	0.9045	0.9800	1.03
COM	WODG_SVC	–	–	–	–	–	–		3.7987	2.2632	4.4217	4.4671	0.1646	0.1193	100	100	7.52	99.76	100	0.9524	1.03
	WDG-T4-0.80lg/$SVC_{alpha=115}{}^0$	1.6563	−1.2422	0.80	23	–	–		2.1640	3.5341	4.1440	4.4651	0.1463	0.1015	97.93	98.55	6.20	97.65	0.6765	0.9577	1.03
	WDG-T4-0.80lg + SVC (−0.250)	1.7098	−1.2823	0.80	24	115.44	−0.250	6	2.1231	3.5136	4.1125	4.4156	0.1325	0.0901	94.12	92.23	5.01	95.12	0.5589	0.9590	1.03
	WDG-T4-0.80lg + SVC (−0.500)	1.8224	−1.3668	0.80	6	117.09	−0.500	29	2.0365	3.4289	4.0569	4.3456	0.1285	0.0845	91.45	90.56	4.84	93.45	0.4443	0.9626	1.03
	WDG-T4-0.80lg + SVC (+0.250)	1.4038	−1.0528	0.80	24	112.25	+0.250	31	2.1655	3.5385	4.1498	4.4561	0.1510	0.1045	97.98	99.25	6.35	98.84	0.6871	0.9567	1.03
	WDG-T4-0.80lg + SVC (+0.500)	1.2041	−0.9031	0.80	31	110.71	+0.500	23	2.2005	3.5986	4.1526	4.4562	0.1525	0.1095	98.23	99.59	6.44	98.92	0.7081	0.9560	1.03
REF	WODG_SVC	–	–	–	–	–	–		3.8369	2.3677	4.5086	4.5486	0.1769	0.1177	100	100	7.83	99.41	100	0.9494	1.03
	WDG-T4-0.80lg/$SVC_{alpha=115}{}^0$	1.3080	−0.9810	0.80	26	–	–		2.5473	3.3639	4.2195	4.5423	0.1545	0.1069	98.64	99.30	6.97	96.45	0.7505	0.9771	1.03
	WDG-T4-0.80lg + SVC (−0.250)	1.3996	−1.0497	0.80	6	115.44	−0.250	30	2.4557	3.3328	4.2107	4.5224	0.1438	0.0959	94.28	94.21	5.91	94.67	0.7081	0.9793	1.03
	WDG-T4-0.80lg + SVC (−0.500)	1.5999	−1.1999	0.80	6	117.09	−0.500	29	2.2647	3.2894	4.1441	4.5125	0.1395	0.0802	92.23	91.56	4.89	92.23	0.6921	0.9844	1.03
	WDG-T4-0.80lg + SVC (+0.250)	1.1376	−0.8532	0.80	26	112.25	+0.250	29	2.5873	3.3939	4.2595	4.5328	0.1605	0.1086	98.86	99.63	6.99	98.86	0.7608	0.9712	1.03
	WDG-T4-0.80lg + SVC (+0.500)	1.0405	−0.7803	0.80	6	110.71	+0.500	6	2.6234	3.4123	4.3256	4.5338	0.1655	0.1123	98.99	99.89	7.09	99.25	0.8023	0.9708	1.03

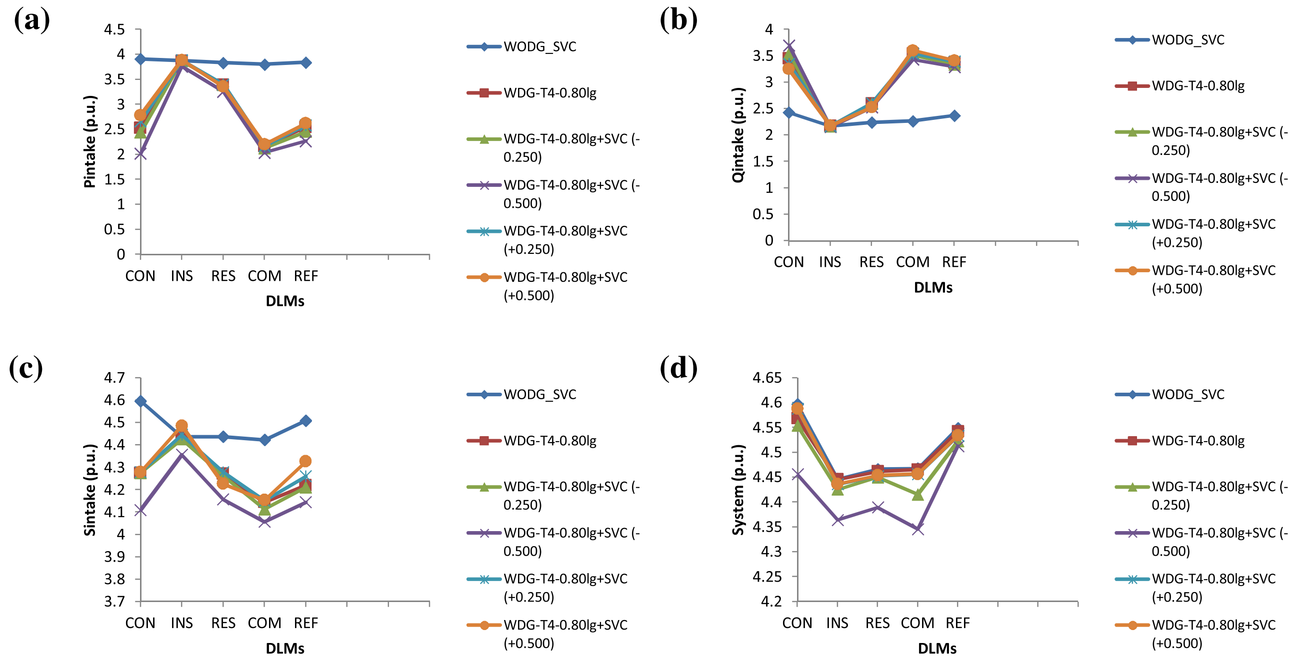

Fig. 16. Pertaining to DG (*i.e.* DG-4 operating at 0.80 lagging power factor) and SVC planned by GA with DLMs (such as CON-INS-RES-COM-REF) in DPSs, profiles of (a) P_{intake}, (b) Q_{intake}, (c) S_{intake} and (d) S_{system}. *'lg' means lagging operating power factor of DG; T4 means DG-4 type of DG.

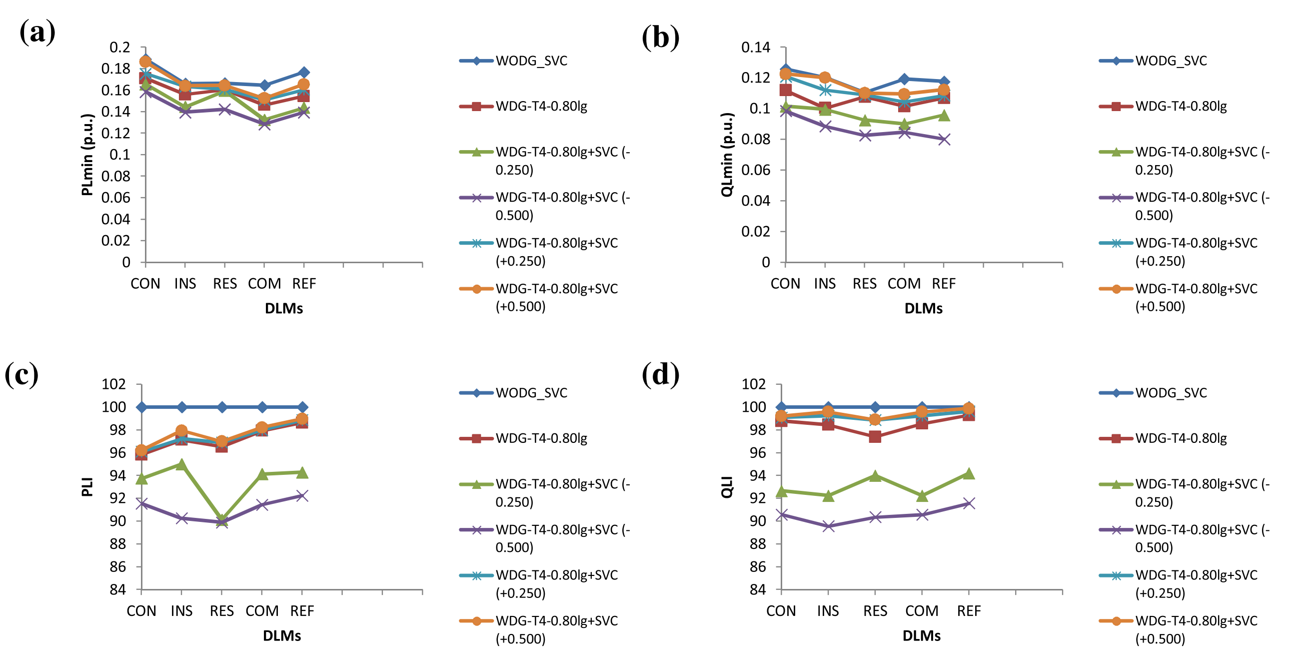

Fig. 17. Pertaining to DG (*i.e.* DG-4 operating at 0.80 lagging power factor) and SVC planned by GA with DLMs (such as CON-INS-RES-COM-REF) in DPSs, profiles of (a) P_{Lmin}, (b) Q_{Lmin}, (c) *PLI* and (d) *QLI*. *'lg' means lagging operating power factor of DG; T4 means DG-4 type of DG.

(ii) *SVC behaves as a resonance mode*: the SVC behaves as a resonance mode means that reactive power is neither delivered nor absorbed from the system bus, hence, all the DPS performance parameters and indices are same as DG-4 type DG (operating at 0.80 lagging power factor),

(iii) *SVC behaves as a load mode*: the SVC behaves as a load mode means that reactive power is absorbed from the system bus, hence, all the DPS performance parameters and indices are poor as compared to DG-4 type DG (operating at 0.80 lagging power factor).

Thus, the DPS performance order would be, in sequence, is follows: DG-4 type DG (operating at 0.80 lagging power factor) and SVC (+0.500) behaves as a load mode means that reactive power is absorbed from the system; >DG-4 type DG (operating at 0.80 lagging power factor) and SVC (+0.250) behaves as a load mode means that reactive power is absorbed from the system; >DG-4 type DG (operating at 0.80 lagging power factor); = DG-4 type DG (operating at 0.80 lagging power factor) and SVC (0.00) behaves as a resonance mode means that reactive power is neither delivered nor absorbed from the system; <DG-4 type DG (operating at 0.80 lagging power factor); <DG-4 type DG (operating at 0.80 lagging power factor) and SVC (−0.250) behaves as a generator mode means that reactive power is delivered to

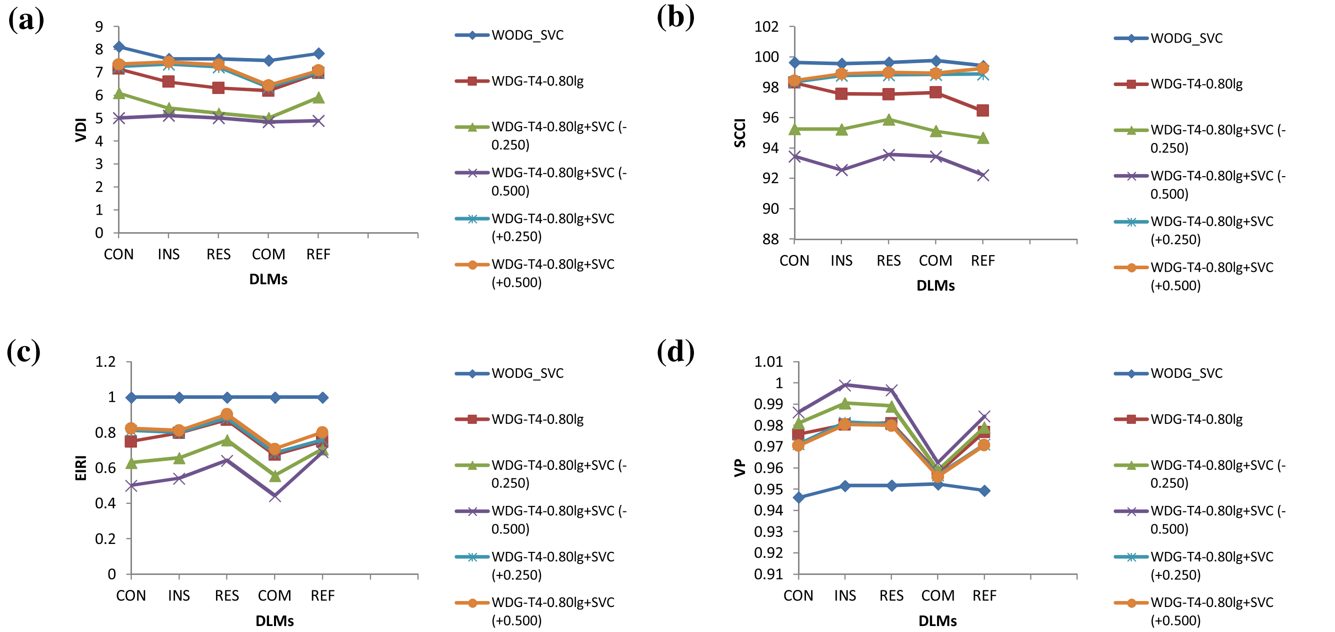

Fig. 18. Pertaining to DG (*i.e.* DG-4 operating at 0.80 lagging power factor) and SVC planned by GA with DLMs (such as CON-INS-RES-COM-REF) in DPSs, profiles of (a) *VDI*, (b) *SCCI*, (c) *EIRI* and (d) *VP*. *'lg' means lagging operating power factor of DG; T4 means DG-4 type of DG.

the system; <DG-4 type DG (operating at 0.80 lagging power factor) and SVC (−0.500) behaves as a generator mode means that reactive power is delivered to the system.

5.5. Comparisons of results

Tables 1–4 show the comparison of results of impact assessment of optimally placed different types of DGs (such as DG-1, DG-2, DG-3 and DG-4) and SVC with DLMs (such as CON-INS-RES-COM-REF load models), as optimized by GA, in DPSs from minimum total real power loss view point. Finally, it is inferred that DG-2 type DG and SVC gives better DPS performance indices as compared to DG-1, DG-3 and DG-4 types DG with DLMs and SVC.

So, the overall DPS performance of DG-2 with SVC is better as compared to DG-1, DG-3and DG-4 with FACTS controller like SVC. Finally, it is observed that DG-2 with SVC is more reliable and efficient as compared to the rest categories of DG such as DG-1, DG-3and DG-4 with SVC.

6. Conclusions and future scope of research work

6.1. Conclusions

This paper presents the impact assessment of optimally placed different types of DGs (such as DG-1, DG-2, DG-3 and DG-4) and FACTS controller like SVC with DLMs by using GA in DPSs from minimum total real power loss viewpoint. This paper focuses on the reduction of the total real power loss of the system. The effectiveness of the proposed methodology is tested on IEEE 37-bus distribution test system. It is observed that the different types of DGs (such as DG-1, DG-2, DG-3 and DG-4) with DLMs and FACTS controller like SVC show different behaviours for DPS performance indices such as *PLI, QLI, VDI, SCCI* and *EIRI*. It is noted that the impact assessment of optimally placed same kinds of DGs such as DG-2 and DG-4 operating at different power factors (varies from 0.80 to 0.99 leading and lagging, respectively) with DLMs and FACTS controller like SVC show the different behaviours for these DPS performance indices.

The research findings of the present article may be summarized as follows:

- This work discusses about the important topic of integration of renewable energy sources such as DGs and FACTS controller with the electricity grid while taking into account different DPS performance indicators.
- It is revealed that DG-2 type DG and SVC gives better DPS performance indices as compared to DG-1, DG-3 and DG-4 types DGs with DLMs and SVC.
- This work would be very much helpful for practitioners working on the implementation aspect of renewable energy (different types of DGs) and inclusion of FACTS controller.
- Building of future electricity grids and inclusion of the different DPS performance indicators for better social welfare, reduction in the environmental pollutant emission, improvement of the technical issues and reduction in the economical burden are some remarkable results of the present research work.

6.2. Recommendations for scope of future research work

The following recommendations as the scope of future research work in this direction may be recommended.

- Similar type of analysis may be taken up while considering minimization of total power intake at substation.
- Improvement of the security aspect may be treated as an objective function, in future.
- In future, utilization of some other AI and hybrid AI techniques for optimal placement and proper coordinated control of DGs with FACTS controller such as STATCOM or distributed-STATCOM in DPSs may be carried out with static load models only and static as well as realistic load models.
- The above mentioned scope of future work may be further extended to static load models with seasonal criterion only and static load models with seasonal criterion as well as realistic load models.

Appendix A

Table A1
Frequency ranges of interactions between different types of DGs and SVC.

S.No.	Frequency ranges	Type of interactions between different types of DGs and SVC
1	0 Hz	Steady-state interactions
2	0–3 or 5 Hz	Electro-mechanical oscillations
3	2–15 Hz	Small-signal or control oscillations
4	10–50/60 Hz	SSR interactions
5	>15 Hz	Electro-magnetic transients, high frequency resonance or harmonic resonance interactions and network resonance interactions

Table A2
Values of relevant factors of DLMs for buses (IEEE 37-bus distribution test system).

Bus no.	A*	B*	C*	Bus no.	A*	B*	C*
1(GSP)	0.0000	0.0000	0.0000	20	0.3000	0.4000	0.3000
2	0.2000	0.5000	0.3000	21	0.3000	0.4000	0.3000
3	0.1500	0.6000	0.2500	22	0.3000	0.4000	0.3000
4	0.2000	0.5000	0.3000	23	0.3500	0.4500	0.2000
5	0.1100	0.3400	0.5500	24	0.2000	0.6500	0.1500
6	0.1500	0.3000	0.5500	25	0.2000	0.6500	0.1500
7	0.3000	0.5000	0.2000	26	0.1500	0.2000	0.6500
8	0.3000	0.5000	0.2000	27	0.1000	0.2500	0.6500
9	0.0800	0.1000	0.8200	28	0.1000	0.3000	0.6000
10	0.0800	0.2000	0.7200	29	0.2500	0.3500	0.4000
11	0.1200	0.2000	0.6800	30	0.5000	0.3500	0.1500
12	0.2500	0.3000	0.4500	31	0.2000	0.3500	0.4500
13	0.2000	0.3500	0.4500	32	0.3000	0.5500	0.1500
14	0.1500	0.3500	0.5000	33	0.2000	0.3500	0.4500
15	0.0500	0.3000	0.6500	34	0.0000	0.0000	0.0000
16	0.0800	0.1000	0.8200	35	0.0000	0.0000	0.0000
17	0.0800	0.2000	0.7200	36	0.0000	0.0000	0.0000
18	0.3000	0.4000	0.3000	37	0.0000	0.0000	0.0000
19	0.3000	0.4000	0.3000	38	0.0000	0.0000	0.0000

A* means$w_{ins_pi_bus} = w_{ins_qi_bus}$, B* means $w_{res_pi_bus} = w_{res_qi_bus}$and C* means$w_{com_pi_bus} = w_{com_qi_bus}$.

Table A3
Exponent values for DLMs [5].

Load models	*alpha*	*βeta*
CON	0.00	0.00
INS	0.18	6.00
RES	0.92	4.04
COM	1.51	3.40
REF	0.91	1.00

Table A4
Type and size of DGs.

Sl. no.	Type	Rating
1	Micro DG	1–5 Kw
2	Small DG	5–5 MW
3	Medium DG	5–50 MW
4	Large DG	50–300 MW

Table A5
SVC data [24–27].

SVC_{alpha} (α) (degree)	$Q_{SVC}(\alpha)$ (p.u.)	Mode of operation of SVC
115.44	−0.250	as SVC load
117.09	−0.500	as SVC load
113.82	0.000	SVC in resonance (floating stage)
112.25	+0.250	as SVC generator
110.71	+0.500	as SVC generator

Table A6
Important pollutants emission of main substation [28].

Pollutants emission of GHG level	CO_2 (kg/MWh)	SO_2 (kg/MWh)	NO_x (kg/MWh)	Particulate matters
Main substations	970	0.6396	0.3129	0.1270

Table A7
Important pollutants emission of different types of DGs [28].

Pollutant emission of GHG level		CO_2 (kg/MWh)	SO_2 (kg/MWh)	NO_x (kg/MWh)	Particulate matters
Different types of DGs	DG-1	490	0.0004536	0.004536	0.000000
	DG-2	825	0.181400	5.21630	0.84820
	DG-3	75	0.0001568	0.001568	0.00000
	DG-4	202	0.0027220	0.004536	0.00000

Table A8
Values of weight factors of pollutants emission indices on merit/priority basis.

Pollutants	Weight factors
Carbon dioxide (CO_2)	$EI_{CO_2} = 0.4$
Sulphur dioxide (SO_2)	$EI_{SO_2} = 0.3$
Nitrogen oxide (NO_x)	$EI_{NO_x} = 0.2$
Particulate matters	$EI_{particulate} = 0.1$

Table A9
Comparisons between GA, PSO and ACO.

Measures	GA	PSO	ACO
Parameters	Crossover rate. Mutation rate. Population size.	Population size Velocity of each particle.	Pheromone evaporation rate.
Convergence	Rapid	Rapid but less than GA	Slow due to pheromone evaporation.
Intensification and diversification component	Crossover, mutation, natural selection.	Local search, fitness.	Pheromone update, probability of selecting next vertex.

Table A10
Values of weight factors of DPS performance indices on merit/priority basis.

Weight factors for PS performance indices	Values as per priority basis
η_1	0.40
η_2	0.30
η_3	0.10
η_4	0.10
η_5	0.10

Table A11
System and load data for IEEE 37-bus (38-node) distribution test system [5–9].

From	To	Line Impedance in p.u.			Load on to node (p.u.)			
		$R_{p.u.}$	$X_{p.u.}$	L	S_L	P_L	Q_L	L_T
1	2	0.000574	0.000293	1	4.6	0.1	0.06	R
2	3	0.00307	0.001564	6	4.1	0.09	0.04	I
3	4	0.002279	0.001161	11	2.9	0.12	0.08	C
4	5	0.002373	0.001209	12	2.9	0.06	0.03	R
5	6	0.0051	0.004402	13	2.9	0.06	0.02	I
6	7	0.001166	0.003853	22	1.5	0.2	0.1	C
7	8	0.00443	0.001464	23	1.05	0.2	0.1	C
8	9	0.006413	0.004608	25	1.05	0.06	0.02	I
9	10	0.006501	0.004608	27	1.05	0.06	0.02	C
10	11	0.001224	0.000405	28	1.05	0.045	0.03	C
11	12	0.002331	0.000771	29	1.05	0.06	0.035	R
12	13	0.009141	0.007192	31	0.5	0.06	0.035	C
13	14	0.003372	0.004439	32	0.45	0.12	0.08	R
14	15	0.00368	0.003275	33	0.3	0.06	0.01	C
15	16	0.004647	0.003394	34	0.25	0.06	0.02	I
16	17	0.008026	0.010716	35	0.25	0.06	0.02	C
17	18	0.004558	0.003574	36	0.1	0.09	0.04	I
2	19	0.001021	0.000974	2	0.5	0.09	0.04	R

Table A11 (*Continued*)

From	To	Line Impedance in p.u.			Load on to node (p.u.)			
		$R_{p.u.}$	$X_{p.u.}$	L	S_L	P_L	Q_L	L_T
19	20	0.009366	0.00844	3	0.5	0.09	0.04	C
20	21	0.00255	0.002979	4	0.21	0.09	0.04	I
21	22	0.004414	0.005836	5	0.11	0.09	0.04	R
3	23	0.002809	0.00192	7	1.05	0.09	0.04	C
23	24	0.005592	0.004415	8	1.05	0.42	0.2	C
24	25	0.005579	0.004366	9	0.5	0.42	0.2	C
6	26	0.001264	0.000644	14	1.5	0.06	0.025	C
26	27	0.00177	0.000901	15	1.5	0.06	0.025	I
27	28	0.006594	0.005814	16	1.5	0.06	0.02	C
28	29	0.005007	0.004362	17	1.5	0.12	0.07	C
29	30	0.00316	0.00161	18	1.5	0.2	0.6	C
30	31	0.006067	0.005996	19	0.5	0.15	0.07	R
31	32	0.001933	0.002253	20	0.5	0.21	0.1	R
32	33	0.002123	0.003301	21	0.1	0.06	0.04	C
8	34	0.012453	0.012453	24	0.5	0	0	
9	35	0.012453	0.012453	26	0.5	0	0	
12	36	0.012453	0.012453	30	0.5	0	0	
18	37	0.003113	0.003113	37	0.5	0	0	
25	38	0.00313	0.003113	10	0.1	0	0	

L = Line number, S_L = Line MVA limit (p.u.), P_L = Real MW load (p.u.), Q_L = Reactive MVAr load (p.u.), L_T = Load type, R = Residential, I = Industrial, C = Commercial.

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