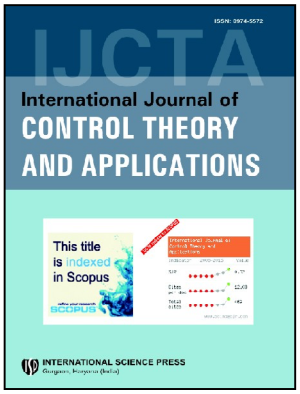

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Simultaneous DG and Capacitor Placement for Energy Loss Minimization with Constant and Time Varying Load Profile

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Abstract: Energy conservation is gaining importance as it helps in bridging the ever increasing gap between generation and demand. Capacitor allocation is often considered as an option to minimize system losses but its impact is limited as it could inject only reactive power. With the recent restructured electricity markets, there is huge proliferation of distributed generation (DG) which drastically changed the loss minimization paradigm. In this context, the impact of DG along with capacitor placement need to be studied in detail as combined placement of these two could result in improved energy loss minimization. Conventional approaches for optimal placement of DG units and/or capacitor units are based on the assumption that network load profile is constant which is unrealistic. Hence optimal sizes and locations found assuming constant load profile would not lead to minimum annual energy loss under actual scenario where load duration curve is varying with time. The aim of this work is to consider the effect of time-varying load profile in determining the optimal DG and/or capacitor sizes and locations. Hence, a new approach based on time-varying load profile is proposed to solve DG and/or capacitor placement problem with an objective to minimize annual energy loss in the distribution system. The efficacy of the proposed approach is verified by carrying out simulations on IEEE 69-bus radial distribution system.

Keywords: Distributed generation, Capacitor placement, Time-varying load profile, Annual energy loss, Harmony Search Algorithm.

I. INTRODUCTION

Growth in energy generation is lagging behind the growing demand due to various reasons like industrial growth, rapid urbanization, increasing affordability of electric gadgets etc. Hence it is imperative to utilize the generated electrical energy efficiently to maximize economic benefits by conserving the energy. Power losses at distribution level are predominant in the system mainly due to low voltage and high currents and partly due to the overload conditions. In this context focus on energy conservation by employing loss reduction methods such as network reconfiguration, capacitor allocation and network reconductoring is increasing. Among these, usage of shunt capacitors along the feeders is very popular as it helps in reducing losses, improving voltage profile of the system and to some extent alleviating line overloading problem. However, its effectiveness is limited as only reactive power is injected in to the network. Another trend gaining popularity is the use of Distributed Generation (DG) for loss reduction which got popularized due to restructuring of electric power system [1]. DG is localized small scale generation capable of injecting active power and providing limited reactive power support. DG allocation can reduce energy losses, increase electric system reliability, reduce peak power generation requirement, reduce line loading for a given system load and enhance voltage profile to a great extent [2, 3]. Supplementing capacitor units with DG will further enhance the above benefits to distribution utilities as both active and reactive power support can be provided locally in the network. However, to reap the benefits, it is important to install DG and capacitor units at optimal locations with optimal sizes.

Many researchers tried to solve DG allocation or capacitor allocation problem using different analytical methods and meta-heuristic based methods. Meta-heuristic techniques such as Artificial Bee Colony (ABC) algorithm [4], Harmony search algorithm (HSA) [5], Flower pollination algorithm [6], Grey Wolf Optimizer [7], improved teaching learning based optimization algorithm [8] were used to solve DG allocation problem to reduce active power loss. Das [9] used Fuzzy-GA method used Plant Growth Simulation algorithm to solve shunt capacitor allocation problem. Bhattacharya and Goswami [10] used Fuzzy method to identify locations and Simulated Annealing to optimize the capacitor sizes for minimizing the loss cost and capacitor cost. A few authors tried to analyze the impact of both DG placement and capacitor in distribution systems. Wang and Zhong [11] proposed a method to optimally allocate DG units and capacitors for network bus voltage improvement. Kai Zou *et al.* [12] used a numerical method to identify optimal locations and employed PSO to minimize investment costs of DG and capacitor units. Mohapatra et al. [13] presented a method using Differential Evolution [DE] for optimal DG and capacitor placement in order to minimize network power loss. Naik et al. [14] used a heuristic approach to solve DG and capacitor allocation problem. Amin et al. [15] used intersect mutation differential evolution to solve DG and capacitor allocation problem to reduce power loss. Muthukumar and Jayalalitha [16] used hybrid heuristic search algorithm to allocate DG and capacitors optimally in a network to minimize loss. All the above mentioned methods assumed constant load profile for system loads.

Most of the methods proposed in literature so far for solving DG and/or capacitor optimization problem assumed constant load profile. The obtained optimal DG and/or capacitor unit's sizes/locations when employed in actual scenario where the loading pattern of a distribution system changes with time (time-varying load profile) results in higher annual energy loss than anticipated. Hence, DG and/or capacitor optimization problem solved with constant load profile does not give a workable solution. To consider time-varying load profile aspect for DG and/or capacitor allocation problem, time-varying load profile over a period of time need to be considered (at least annual) for analysis and hence, energy loss minimization is chosen as objective instead of power loss minimization. In this realistic approach which considers the time-varying load profile aspect, actual annual energy loss is computed by repeated load flow runs on hourly basis considering load changes and the obtained losses are aggregated. However, a few authors tried to address this time-varying load profile aspect while solving optimal DG allocation problem. Wang and Nehrir [17] considered both time-invariant as well as time-varying load aspects while obtaining optimal location of DG in order to minimize loss. Typical daily average demand profile is used to characterize time-varying load aspect for the entire year. However, DG size was not optimized and seasonal daily averaged load demand profiles were not considered for analysis. Dan Zhu et al. [18] used an exhaustive search approach for optimal DG placement with time-varying loads to minimize loss and increase reliability. The actual load curve is approximated to three or four load windows, in which the loading condition of each window is assumed to be relatively constant. However, complexity of exhaustive search increases as the number of load windows (states) for accurate representation of the load curve increases. Atwa and Saadany [19] presented a probabilistic generation-load model that considers all the wind based DG output power and load levels with their respective probabilities. However, time-varying load profile aspect which is critical was ignored by authors while solving simultaneous DG and capacitor allocation problem, and therefore needs further attention.

Hence, in this work a new approach for deploying optimum DG and/or capacitor units which considers the varying load duration curve aspect for system loads is proposed. HSA is used to solve the optimal site and size problem of multiple DG and capacitor units to minimize annual energy loss. Salient features of the proposed approach are: (i) optimal locations and sizes are determined simultaneously to install multiple DG and/or capacitor units in one go and (ii) time-varying load profile of loads are taken in to account. Proposed approach is employed on IEEE 69 bus system to check its efficacy. Proposed approach is used to find optimal sizes and locations for different scenarios viz., optimal DG placement, optimal capacitor placement, optimal DG installation after capacitor placement, optimal capacitor placement after DG installation and simultaneous installation of DG and capacitor units. Proposed approach is compared with conventional approach which optimizes locations and sizes of DG and/or capacitor units for the above scenarios, assuming constant load profile for system loads.

The content in the paper is organized as: Section II discusses problem formulation, Section III explains Proposed method for DG and/or capacitor allocation, Section IV presents results and discussion, and Section V gives conclusions.

II. PROBLEM FORMULATION

To calculate annual energy loss in a distribution system, energy losses on hourly basis at each node need to be aggregated. IEEE 69-bus test feeder which is chosen to evaluate the proposed approach does not furnish hourly load data at each node. Hence, load data specified in IEEE test system is assumed as peak demand and demands for each hour are assumed to follow hourly load pattern of IEEE-RTS [20]. IEEE-RTS considers seasonal, weekly and daily variations for the loads. To compute annual energy loss, daily load patterns are taken in to account over 365 days. The time-varying load is discretized into hourly load variations, so effectively there will be 8,760 (=365*24) load states per annum. To compute annual energy loss, power flow analysis for 8,760 times need to be performed, which is tedious. The analysis is simplified by representing the total load states by five equivalent states (r) with corresponding probabilities (P_{Lg}), using K-means clustering technique [21]. Five equivalent load states were chosen which provides a reasonable trade-off between accuracy and fast numerical computation. Table I shows load equivalent states and their probabilities. For the sake of simplicity it is assumed that all the system nodes are assumed to follow the same load pattern. Further the yearly load profile curve is assumed to be more or less repetitive in nature. Figure 1 shows the typical load profiles of a weekday and weekend in winter and summer seasons.

Table 1
Load states with probabilities

Load state (g)	*% of peak load*	*Probability (P_{Lg})*
1	84.14	0.1424
2	73.38	0.1825
3	63.03	0.2454
4	51.99	0.2429
5	42.60	0.1868

2.1. Mathematical model

2.1.1. Proposed approach (Time-varying load profile)

The following equations [22] are derived from the feeder diagram depicted in Figure 2 and are used to compute power flows with DG and capacitor units considering time-varying load profile aspect.

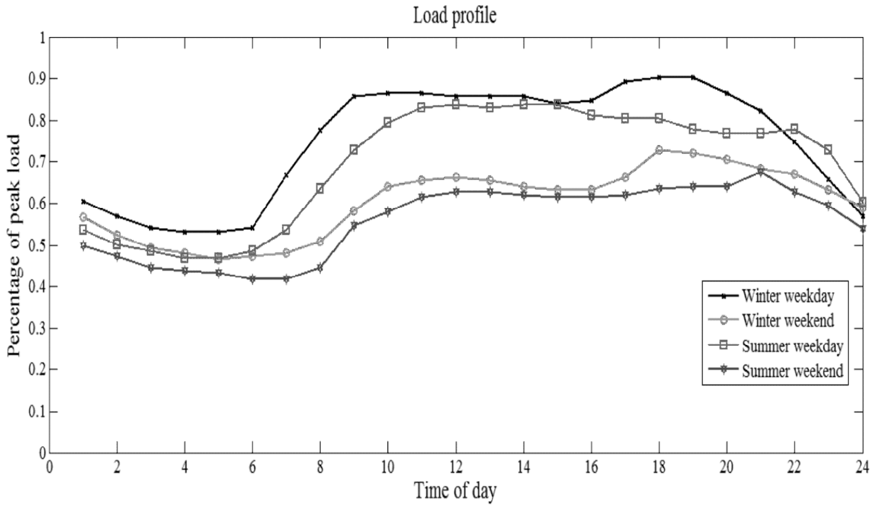

Figure 1: Load profile of a weekday and weekend in winter and summer seasons

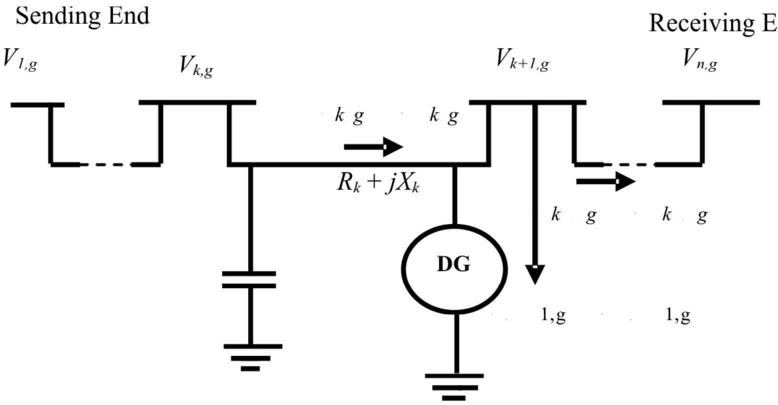

Figure 2: SLD of a feeder

$$P_{k+1,g} = P_{k,g} - \frac{R_k}{\left|V_{k,g}\right|^2}\left\{P_{k,g}^2 + Q_{k,g}^2\right\} - P_{Lk+1,g} + P_{DG,k+1} \tag{1}$$

$$Q_{k+1,g} = Q_{k,g} - \frac{X_k}{\left|V_{k,g}\right|^2}\left\{P_{k,g}^2 + Q_{k,g}^2\right\} - Q_{Lk+1,g} + Q_{DG,k+1} + Q_{C,k} \tag{2}$$

$$\left|V_{k+1,g}\right|^2 = \left|V_{k,g}\right|^2 + \frac{R_k^2 + X_k^2}{\left|V_{k,g}\right|^2}\left(\mathrm{P}_{k,g}^2 + Q_{k,g}^2\right) - 2\left(R_k P_{k,g} + X_k Q_{k,g}\right) \tag{3}$$

$$k = 0,1,2....n$$

where, $P_{k,g}$ and $Q_{k,g}$ denote active and reactive powers flowing through node k during state g, $P_{Lk+1,g}$ and $Q_{Lk+1,g}$ denote active and reactive load powers flowing out of bus $k+1$ during state g, $P_{DG,k+1}$ and $Q_{DG,k+1}$ correspond to real and reactive powers supplied by DG at $(k+1)^{th}$ bus, $Q_{C,k}$ is capacitive power injected at k^{th} bus and R_k and X_k denote the branch resistance and reactance between nodes k and $k+1$ respectively.

Power loss in the branch connecting nodes k and k+1 during state g is given by

$$P_{Loss,g}(k,k+1) = R_k.\frac{(P_{k,g}^2 + Q_{k,g}^2)}{\left|V_{k,g}\right|^2} \tag{4}$$

$P_{TLoss,g}$, the total active power loss is given by

$$P_{TLoss,g} = \sum_{k=1}^{n-1} P_{Loss,g}(k,k+1) \tag{5}$$

where n indicates highest bus number in the system.

Energy loss during state g is

$$E_{Loss,g} = P_{TLoss,g} \times P_{Lg} \times 8760 \tag{6}$$

where P_{Lg} is the probability of load to be in state g and *8760* is the number of annual hours.

Annual energy loss minimization is chosen as the objective

$$Objective function = \min \sum_{g=1}^{r} E_{TLoss,g} \tag{7}$$

where r is the number of load states.

Equality constraints

Real and reactive power balance given by (1) and (2) and voltage equation given by (3) are to be satisfied.

Inequality constraints

1. Current limit:

$$\left|I_{k,k+1}\right| \le \left|I_{k,k+1,\max}\right| \tag{8}$$

where $I_{k,k+1}$ and $I_{k,k+1,max}$ are the current flow through the branch and the current limit of the branch connecting buses k and k+1 respectively.

2. DG unit limit and Total DG capacity limit:

$$S_{DG,\min} \le S_{DG,k+1} \le S_{DG,\max} \tag{9}$$

$$S_{DG,Total} \le x * S_{D,Total} \tag{10}$$

where $S_{DG,k+1}$ is the installed DG unit size in kVA at $k+1^{th}$ bus, $S_{DG,min}$ is the minimum DG unit size in kVA, $S_{DG,max}$ is the maximum DG unit size in kVA, $S_{DG,Total}$ is the aggregate of all installed DG unit sizes in kVA, $S_{D,Total}$ is the total system demand including losses in kVA and x is the DG penetration level whose range is between 0 and *1*. DG penetration level (x) is the ratio of total DG active power injected to total system active load. If DG unit to be installed is capable of injecting active power only then reactive power component in (9) is zero and not considered in (10).

3. Capacitor limit:

$$Q_{C,\min} \le Q_{C,k+1} \le Q_{C,\max} \tag{11}$$

$$Q_{C,Total} \leq y * Q_{D,Total} \tag{12}$$

where $Q_{C,k+1}$ is the installed capacitor unit size in kVAR at $k+1^{th}$ bus, $Q_{C,min}$ is the minimum size of capacitor unit in kVAR, $Q_{C,max}$ is the maximum size of capacitor unit in kVAR, $Q_{C,Total}$ is the aggregate of all installed capacitor unit sizes in kVAR, $Q_{D,Total}$ is the total system kVAR demand including losses and y is the capacitor penetration level whose range is between 0 and 1.

The objective function (7) subjected to the above equality and inequality constraints is solved/optimized using a meta-heuristic algorithm to determine optimal DG and capacitor unit sizes along with locations.

2.1.2. Conventional approach (Constant load profile)

While determining optimal DG, capacitor unit sizes and their locations considering constant load profile, equations (1) to (5) are to be used by considering $g = r = 1$ since it is assumed that there is only one load state. Minimization of total power loss is chosen as the objective function given by (13)

$$Objective\ function = min \sum_{g=1}^{r} P_{TLoss,g} \tag{13}$$

subjected to constraints specified in (8) to (12).

III. METHODOLOGY

This section describes the steps involved in proposed and conventional approaches for solving optimal DG allocation and/or capacitor allocation problem. Usage of HS Algorithm for both proposed and conventional approaches is also explained in this section.

3.1. Proposed approach

Proposed approach which considers time-variant load profile is formulated as:

1. Using K-means clustering 8760 load states are clustered in to five equivalent states and respective probabilities (P_{Lg}) are found.
2. By employing HSA, optimal sizes and locations of DG and/or capacitors are found to minimize annual energy losses.

3.2. Conventional approach

Using conventional approach, HSA is used to obtain optimum DG and/or capacitor sizes and locations assuming constant load profile to minimize network power loss.

Actual energy loss is computed with DG and/or capacitor sizes and locations obtained, by running load flow hour by hour for the entire year changing hourly load as per time- varying load profile. Then power losses obtained for each hour are aggregated to obtain annual energy losses.

3.3. HS Algorithm application for Proposed and Conventional approach

The advantage of HSA is its adaptability and simplicity in solving different types of problems. In earlier works, Reconfiguration and DG installation problems were solved successfully using HSA [7]. HSA involves steps such as: initialization of the HS parameters, initialization of solution vectors which are referred as harmony memory, updating the harmony memory based on best vectors. The above steps are clearly explained in [23].

For both the approaches application of HSA is similar. In either approach, solution vector has both potential locations and sizes of DG and/or capacitors units. A typical solution vector HV^1 of length $2N$ is formed as in (14):

$$HV^1 = \left[\underbrace{L_1^1 \quad L_2^1 \quad .... \quad L_N^1}_{DG \text{ and/or capacitor Locations}} \quad \underbrace{S_1^1 \quad S_2^1 \quad .... \quad S_N^1}_{DG \text{ and/or capacitor Sizes}} \right] \tag{14}$$

where $S_1^1 \quad S_2^1 ... \ S_N^1$ are sizes of DG and/or capacitor units deployed at $L_1^1 \ L_2^1 .... \ L_N^1$ nodes respectively.

In a similar manner other solution vectors are randomly generated such that solution vectors of *HMS* (Harmony memory size) number are available in harmony memory (HM) as shown in (15).

$$HM = \begin{bmatrix} L_1^1 & L_2^1 & \cdots & L_N^1 & S_1^1 & S_2^1 & \cdots & S_N^1 \\ L_1^2 & L_2^2 & \cdots & L_N^2 & S_1^2 & S_2^2 & \cdots & S_N^2 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ L_1^{HMS} & L_2^{HMS} & \cdots & L_N^{HMS} & S_1^{HMS} & S_2^{HMS} & \cdots & S_N^{HMS} \end{bmatrix} \tag{15}$$

The objective function “Energy loss” value is computed for each solution vector of *HM* and vectors in *HM* are sorted in ascending order according to their objective function values. Solution vectors in HM are updated based on HS algorithm rules. Flow charts of the conventional and proposed approaches for solving DG and/or capacitor allocation problems are depicted in Figure 3 and Figure 4 respectively.

IV. RESULTS AND DISCUSSION

The efficacies of the proposed and conventional approaches are verified by applying on IEEE 69-bus test system. Six scenarios are considered for testing.

Scenario I – Without any DG or capacitor units installed in distribution system

Scenario II – Only capacitor units installed

Scenario III – Only DG units installed

Scenario IV – DG Installation after Capacitor placement

Scenario V – Capacitor installation after DG placement

Scenario VI – Simultaneous DG and Capacitor Installation

Different combinations of HS algorithm parameter values are tried in this study and the best combination among them with *HMS*=100, *HMCR*=0.9, *PAR* (Pitch adjustment ratio) =0.3, and *NI* (maximum number of improvisations) =100 is used.

Dispatchable DG units are considered for analysis and capacity factor of the installed DG units are assumed to be unity. For testing the proposed and conventional approaches, two cases of 30% and 50% DG penetration levels are tried in this work. No limit is kept on total maximum reactive power injection by capacitors. In all scenarios it is ensured that feeder current limits are not violated. Type1 and Type2 DG units are considered for analysis. Type1 DG units are capable of supplying only active power. Type2 DG units are synchronous generators capable of delivering both active and reactive powers operating at 0.85 p.f. An index to measure the effectiveness of DG and/or capacitor placement on voltage profile improvement is formulated as shown in (16).

$$\% \ V_{index} = \frac{\sum_{i=1}^{8760} \sum_{j=2}^{n} (1 - abs(v_{ij}))}{(n-1) \times 8760} \times 100 \tag{16}$$

where v is the bus voltage.

4.1. IEEE 69-bus system

The active power demand is 3802.19 kW and reactive power demand is 2694.06 kVar for 69-bus sytem [7]. The annual energy loss assuming constant load profile is 1970.8248 MWh (obtained by multiplying base case loss (224.98 kW) with annual number of hours (8760)), whereas the actual energy loss considering time-varying load profile is 739.74 MWh which is obtained by performing load flow analysis 8760 times and aggregating the hourly losses. The computed annual energy loss when the 8760 states are grouped into five equivalent states is 737.27 MWh, which is again very close to that obtained with hourly computation.

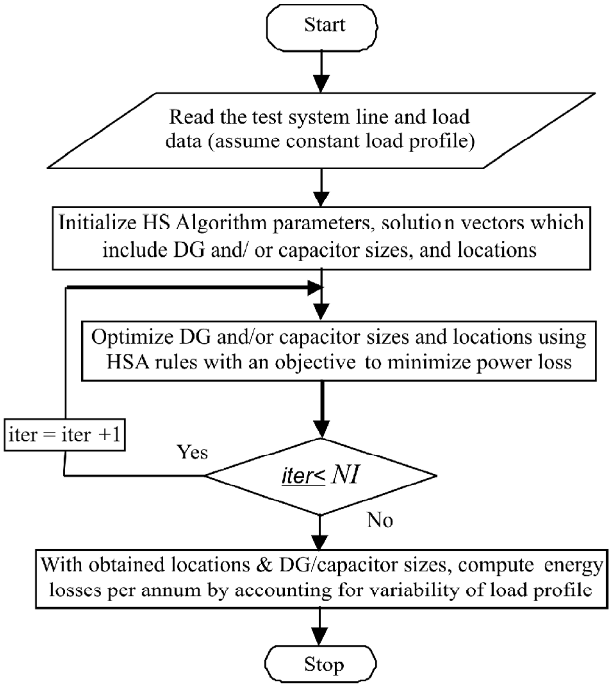

Figure 3: Flow chart of the conventional approach

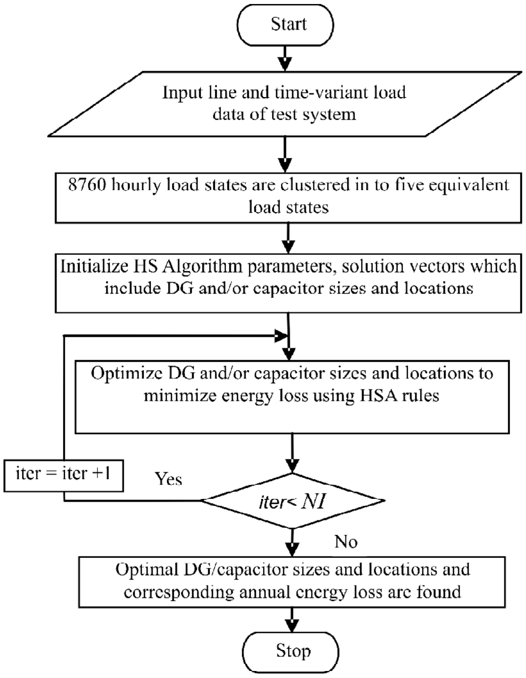

Figure 4: Flow chart of the proposed approach

4.1.1. Simulation results with Type 1 DG

Results obtained with both approaches are presented in Table 2. With proposed approach the DG and/or capacitor sizes required to be installed are less and the corresponding energy loss is also considerably less compared with conventional approach for all scenarios. Scenarios IV, V and VI result in almost same loss reduction. However, the ratio of percentage energy loss reduction to total MVA injected is highest with scenario VI which is shown in Figure 5.

4.1.2. Simulation results with Type 2 DG

From Table 3 it is evident that percentage energy loss reduction and DG/capacitor sizes obtained with proposed approach are smaller compared to the ones obtained with conventional approach.

With 30% DG penetration, scenarios V and VI lead to higher loss reduction with total DG and capacitor size required being less for scenario VI. With 50% DG penetration, scenarios III, V and VI lead to higher loss reduction. However, ratio of percentage energy loss reduction to total MVA injected is high for both scenario III and VI. But the overall cost of equipment installed with scenario VI will be less as its corresponding DG size is less. This indicates the effectiveness of simultaneous placement of DG and capacitors. Further, the ratio of percentage energy loss reduction to total MVA injected is highest with scenario VI closely followed by scenario III as shown in Figure 6.

Table 2
Results of IEEE 69-bus system with type1 DG

		Conv. Approach	*Proposed Approach*	*Conv. approach*	*Proposed approach*
		30% DG penetration		50% DG penetration	
Base case (Scenario-I)	Energy Loss (kWh)	739.74			
	%V_{index}	1.6149			
Only Capacitor Placement (Scenario- II)	Capacitor sizes in kVAR (Bus Number)	0.300 (11)	0.750 (61)	0.300 (11)	0.750 (61)
		1.200 (61)	0.300 (11)	1.200 (61)	0.300 (11)
		0.300 (18)	0.150 (27)	0.300 (18)	0.150 (27)
	Power Loss (kW)	145.28	—	145.28	—
	Energy Loss (MWh)	581.14	499.70	581.14	499.70
	% Energy Loss Reduction	**21.44**	**32.45**	**21.44**	**32.45**
	%V_{index}	1.0021	1.2052	1.0021	1.2052
	Total Size	1.8	1.2	1.8	1.2
Only DG Installation (Scenario-III)	DG sizesin MW (Bus Number)	0.552 (61)	0.652 (61)	1.243 (61)	1.0360 (62)
		0.188 (65)	0.282 (64)	0.316 (65)	0.3260 (10)
		0.400 (62)	0.206 (19)	0.342 (20)	0.2430 (18)
	Power Loss (kW)	102.58	—	75.29	—
	Energy Loss (kWh)	306.62	282.55	339.42	266.54
	% Energy Loss Reduction	**58.55**	**61.80**	**54.12**	**63.97**
	%V_{index}	0.7952	0.6825	0.3503	0.4450
	Total Size	1.1407	1.1407	1.9010	1.605
DG Installation after Capacitor placement (Scenario-IV)	Capacitor sizes in kVAR (Bus Number)	0.300 (11)	0.750 (61)	0.300 (11)	0.750 (61)
		1.200 (61)	0.300 (11)	1.200 (61)	0.300 (11)
		0.300 (18)	0.150 (27)	0.300 (18)	0.150 (27)
	DG sizesin MW (Bus Number)	0.290 (64)	0.514 (62)	0.346 (22)	0.467 (50)
		0.688 (61)	0.378 (61)	0.994 (61)	1.006 (61)
		0.162 (61)	0.246 (18)	0.561 (62)	0.304 (22)
	Power Loss (kW)	33.11	—	8.93	—
	EnergyLoss (kWh)	171.43	69.77	204.03	54.10
	% Energy Loss Reduction	**76.83**	**90.57**	**72.42**	**92.69**
	%V_{index}	0.4386	0.3703	0.5774	0.3256
	Total Size (DG/Cap)	1.1407/1.8	1.1380/1.2	1.9011/1.8	1.7770/1.2
Capacitor installation after DG placement (Scenario-V)	Capacitor sizes in kVAR (Bus Number)	0.150 (25)	0.150 (18)	0.300 (66)	0.150 (22)
		0.300 (68)	0.750 (61)	0.300 (18)	0.750 (61)
		1.200 (61)	0.150 (12)	1.200 (61)	0.150 (12)
	DG sizesin MW (Bus Number)	0.552 (61)	0.652 (61)	1.243 (61)	1.036 (62)
		0.188 (65)	0.282 (64)	0.316 (65)	0.326 (10)
		0.401 (62)	0.207 (19)	0.342 (20)	0.243 (18)
	Power Loss (kW)	34	—	8.97	—
	EnergyLoss (kWh)	161.87	64.95	207.63	51.74
	% Energy Loss Reduction	**78.12**	**91.22**	**71.93**	**93.00**
	%V_{index}	0.4699	0.3974	0.5771	0.3187
	Total Size (DG/Cap)	1.1407/1.65	1.1407/1.05	1.9011/1.8	1.605/1.05
DG simultaneously with Capacitor Installation (Scenario-VI)	Capacitor sizes in kVAR (Bus Number)	0.300 (20)	0.75 (62)	0.300 (22)	0.150 (21)
		0.300 (61)	0.15 (12)	0.150 (68)	0.750 (61)
		0.900 (61)	0.15 (20)	1.200 (62)	0.150 (12)
	DG sizesin MW (Bus Number)	0.255 (61)	0.652 (61)	0.364 (20)	0.518 (61)
		0.450 (64)	0.282 (64)	0.589 (62)	0.329 (17)
		0.435 (63)	0.206 (19)	0.948 (61)	0.507 (61)
	Power Loss (kW)	35.09	—	9.93	—
	EnergyLoss (kWh)	162.77	66.83	198.20	54.81
	% Energy Loss Reduction	**78.00**	**90.96**	**73.21**	**92.59**
	%V_{index}	0.4796	0.3958	0.5613	0.3306
	Total Size(DG/Cap)	1.1407/1.5	1.1407/1.05	1.9011/1.65	1.3540/1.05

Table 3
Results of IEEE 69-bus system with type2 DG (0.85 p.f.)

		Conv. Approach	*Proposed Approach*	*Conv. approach*	*Proposed approach*
		30% DG penetration		50% DG penetration	
Base case (Scenario-I)	Energy Loss (kWh)	739.74			
	%Vindex	1.6149			
Only Capacitor Placement (Scenario-II)	Capacitor sizes in kVAR (Bus Number)	0.300 (11)	0.750 (61)	0.300 (11)	0.750 (61)
		1.200 (61)	0.300 (11)	1.200 (61)	0.300 (11)
		0.300 (18)	0.150 (27)	0.300 (18)	0.150 (27)
	Energy Loss (MWh)	581.14	499.70	581.14	499.70
	% Loss Reduction	**21.44**	**32.45**	**21.44**	**32.45**
	$\%V_{index}$	1.0021	1.2052	1.0021	1.2052
	Total Size	1.8	1.2	1.8	1.2
Only DG Installation (Scenario-III)	DG Sizes in MW (Bus Number)	0.360 (63)	0.405 (62)	0.782 (63)	0.418 (10)
		0.773 (61)	0.749 (61)	1.129 (61)	0.247 (24)
		0.265 (64)	0.244 (19)	0.419 (21)	1.269 (61)
	Energy Loss (kWh)	111.10	76.57	167.84	51.84
	% Loss Reduction	**84.98**	**89.65**	**77.31**	**92.99**
	$\%V_{index}$	0.6257	0.4418	0.5138	0.3195
	Total Size	1.3980	1.3981	2.3301	1.9340
DG Installation after Capacitor placement (Scenario-IV)	Capacitor sizes in kVAR (Bus Number)	0.300 (11)	0.750 (61)	0.300 (11)	0.750 (61)
		1.200 (61)	0.300 (11)	1.200 (61)	0.300 (11)
		0.300 (18)	0.150 (27)	0.300 (18)	0.150 (27)
	DG Sizesin MW (Bus Number)	0.852 (61)	0.190 (64)	1.145 (61)	0.532 (50)
		0.199 (21)	0.744 (61)	0.415 (20)	0.251 (18)
		0.347 (64)	0.236 (18)	0.359 (64)	0.839 (61)
	Energy Loss (kWh)	470.62	178.30	618.18	174.78
	% Loss Reduction	**36.38**	**75.90**	**16.43**	**76.37**
	$\%V_{index}$	0.3766	0.3398	0.6973	0.3467
	Total Size(DG/Cap)	1.3980/1.8	1.17/1.05	1.9190/1.8	1.622/1.05
Capacitor installation after DG placement (Scenario-V)	Capacitor sizes in kVAR (Bus Number)	0.450 (61)	0.450 (49)	0.300 (12)	0.150 (61)
		0.150 (21)	0.150 (12)	0.600 (49)	0.300 (49)
		0.450 (12)	0.150 (61)	0.150 (64)	0.150 (53)
	DG Sizes in MW (Bus Number)	0.360 (63)	0.405 (62)	0.782 (63)	0.418 (10)
		0.773 (61)	0.749 (61)	1.129 (61)	0.247 (24)
		0.265 (64)	0.244 (19)	0.419 (21)	1.269 (61)
	Energy Loss (kWh)	168.73	59.93	208.86	50.93
	% Loss Reduction	77.19	91.90	71.77	93.11
	$\%V_{index}$	0.4495	0.3795	0.5993	0.3166
	Total Size(DG/Cap)	1.3980/1.05	1.3981/0.75	2.3301/1.05	1.9340/0.600
DG simultaneously with Capacitor Installation (Scenario-VI)	Capacitor sizes in kVAR (Bus Number)	0.45 (11)	0.150 (59)	0.300 (12)	0.150 (49)
		0.45 (62)	0.150 (11)	0.150 (63)	0.150 (11)
		0.15 (21)	0.300 (49)	0.450 (50)	0.150 (53)
	DG Sizes in MW (Bus Number)	0.588 (63)	0.555 (61)	0.437 (20)	0.401 (17)
		0.396 (64)	0.318 (18)	0.360 (64)	0.234 (64)
		0.414 (61)	0.522 (61)	1.533 (61)	1.022 (61)
	EnergyLoss (kWh)	172.89	61.83	197.93	51.25
	% Loss Reduction	**76.63**	**91.64**	**73.24**	**93.07**
	$\%V_{index}$	0.4684	0.3680	0.5982	0.3214
	Total Size(DG/Cap)	1.3980/1.05	1.3950/0.6	2.3301/0.9	1.6570/0.45

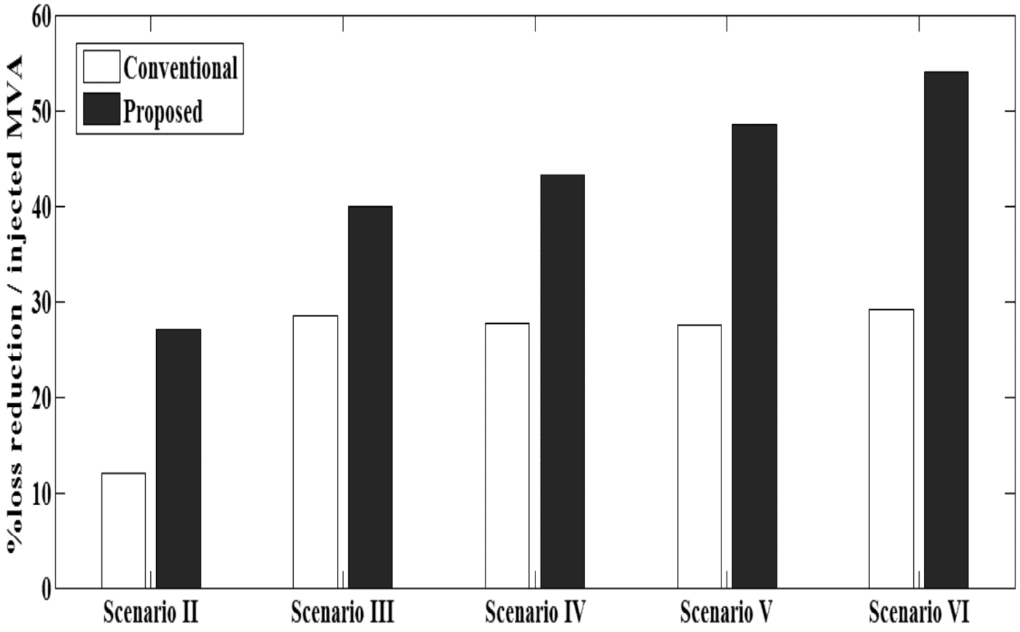

Figure 5: Comparison of different scenarios with Type1 DG for 69-bus system with 50 % DG penetration

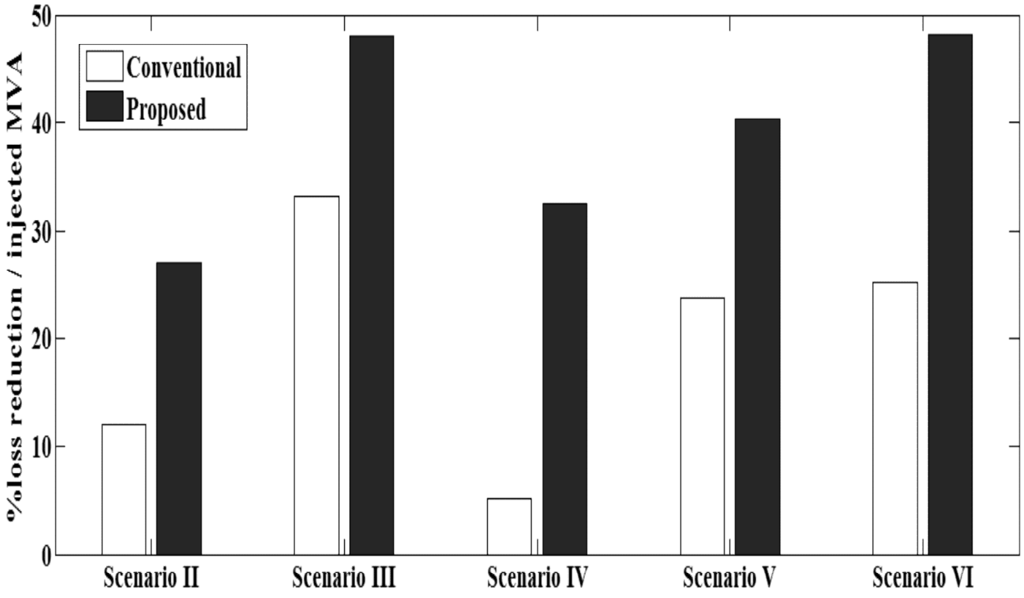

Figure 6: Comparison of different scenarios with Type2 DG for 69-bus system with 50 % DG penetration

4.2. Comparison

In previous works conventional approach using meta-heuristic algorithms such as GA, Fuzzy-GA, PSO and heuristic algorithms is used to find optimal configurations for different scenarios. Performance of different scenarios solved using proposed approach with HSA is compared with the ones available in literature to highlight the performance of proposed approach. From Tables 4 it can be observed that capacitor placement without considering time-varying profile aspects for load won’t result in significant loss reduction.

Table 4
Comparison of results for Scenario II

		69-bus	
Method	*[9]*	*[24]*	*Proposed approach*
Capacitor capacity in MVAr (Bus number)	0.7 (61) 0.8 (64) 0.1 (59)	0.90 (61) 0.45 (15) 0.45 (60)	0.15 (21) 0.3 (11) 0.75 (61)
% Power loss reduction	30.39	34.67	—
Energy loss in MWh	728.25*	620.46*	496.49

* Computed energy loss considering time-varying load profile

V. CONCLUSIONS

A new approach which considers time-varying load profile aspect for system loads is used to obtain optimal DG and/or capacitor units sizes and locations for minimizing annual energy loss. The proposed approach employs HSA to install multiple DG and/or capacitor units optimally in a distributed network. Major contributions of this work are: (1) time-varying load profile is considered for the system loads while solving DG and/or capacitor optimization problem and (2) all possible combinations of DG and capacitor placement were tried for loss minimization and their effectiveness is tested. It is shown that DG with capacitor placement (scenario VI) and capacitor placement after DG installation (scenario V) result in lesser annual energy loss. Supplementing a Type1 DG with capacitors in the network results in huge loss reduction and improved voltage profile; however, with Type2 DG, the effect of capacitor placement on loss reduction is minimal. Further, DG with capacitor placement (scenario VI) is the most effective method as the loss reduction to injected MVA ratio is the highest. Results with Proposed approach and conventional approach are compared to demonstrate that considering time-varying load profile significantly affects the optimal locations and sizing of DGs and capacitors and significantly enhances the loss reduction.

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