A Harmony Search-Based Approach for Real-Time Volt & Var Control in Distribution Network by Considering Distributed Generations Units

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Abstract**—**In recent decades, the development of telecommunications infrastructure has led to the rapid exchange of data between the distribution network components and the control center in many developed countries. Considering the numerous benefits of the Distributed Generators (DGs), these changes have made more motivations for distribution companies to utilize these kinds of generators more than ever before. The Volt & Var control in distribution networks is one of the greatest control plans which can be influenced via DGs. In this study, a new approach is presented for the Volt & Var control which the output reactive powers of the DGs, Static Var Compensators (SVCs), Load Tap Changers (LTCs), Interruptible Load (IL), and the settings of the local controllers are selected as control variables. The proposed approach is a non–linear optimization problem; hence, a novel and robust meta–heuristic algorithm based on the Harmony Search Algorithm (HSA) is presented with high-speed converge. Also, this paper presents an approach to incorporate the model of the DGs and SVCs in the load flow equations of distribution systems. The feasibility and effectiveness of the proposed approach are illustrated on a real–life distribution network, part of the Tehran province electrical distribution network.

Keywords**— Distributed Generation (DG), Distribution Network, Particle Swarm Optimization (PSO), Volt / Var control.**

I. INTRODUCTION

Nowadayds, due of decaying fossil fuels and earth thermal problems, utilization of Distributed Generations (DGs) has grown. For some reasons, including transmission lines loss, high reliability and economic problems, Most of DGs are linked to the distribution network. Hence, these networks convert into active networks, and control of them is not possible with traditional approaches [1]. One of the important problems of network is control of voltage and reactive power. In general, control of voltage is performed by voltage regulators, On Load Tap Changer (OLTC), and shunt capacitors. Many researches have been accomplished on voltage control. In Ref. [2] control of voltage methods is reported. In Ref. [3] coordination between local and central controllers is presented. In Ref. [4] the effect of distribution generation on main transformer tap performance is proposed.

In above-mentioned papers control of voltage problem has been solved by single-objective method. However, automation of power network and use of smart metering devices lead to have real time control of voltage. Real-time control of voltage in the transmission network is investigated by fuzzy logic in Ref. [5]. Furthermore, in Ref., [6], a real-time control method is presented by regarding distribution capacitors. Hence, this paper proposes a new approach for real-time control of voltage and reactive power in the network by considering DGs, voltage regulators, OLTC, Static Var Compensator (SVC). In this proposed methodology, hourly state estimation is regarded to determine state variables. In addition, control of voltage problem has been used fuzzy set theory to do a multi-objective method.

II. STATIC STATE ESTIMATION (SSE)

As earlier noted, to do a suitable monitoring and optimization tool in networks by considering DGs, it should be made some especial control methods. Static State Estimation (SSE) in is the preliminary and essential tool to perform this requirement. The SSE can make effective information support for online functions, including optimal schedule, security assessment, preventive control, and reconfiguration [8]. This paper uses load estimation according to Table 1 for hourly real-time control of voltage.

III. PROPOSED APPROACH FOR REAL-TIME CONTROL OF VOLTAGE

The proposed approach for real-time control of voltage is based on concurrent coordination DGs, voltage regulators, OLTC, and SVC.

Table 1. Estimated hourly load

T (hour)	Step	T (hour)	Step
1	% 67	13	% 95
2	% 63	14	% 95
3	% 60	15	% 93
4	% 59	16	% 94
5	% 59	17	% 99
6	% 60	18	% 100
7	% 74	19	% 100
8	% 86	20	% 96
9	% 95	21	% 91
10	% 96	22	% 86

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11	% 96	23	% 74
12	% 95	24	% 63

The SSE estimation is accomplished for determining loads, buses voltage, line current, etc., in control center to users and operators. If the limitations are violated, the process will be do again and then, variables including active power of DGs, reactive power of SVC, tap position of voltage regulators and OLTC and state of capacitors will be calculated to meet all limitations. The objectives functions are optimization of voltage violation, network losses, and generation cost of active power. These objectives are presented in Equation (1) to Equation (3), respectively [9].

Min:

$$F_1 = \sum_{i=1}^{nbus} \left| V_i^{ref} - V_i \right| \tag{1}$$

$$F_2 = \sum_{i=1}^{nbran} R_i \left| I_i \right|^2 \tag{2}$$

$$F_3 = Pr_h . P_s + C_{DG} . P_{DG} \tag{3}$$

decision variables:

$$x = \left[\overline{Tap}, \overline{U_c}, \overline{Q_{DG}}, \overline{Q_{svc}} \right]_{1\times N} \tag{4}$$

where:

$$\overline{Tap} = [Tap_1, Tap_2, ..., Tap_i]_{1\times N_t}, \forall i = 1,..., N_t \tag{5}$$

$$\overline{U_c} = [U_{c1}, U_{c2}, ..., U_{ci}]_{1\times N_c}, \forall i = 1,..., N_c \tag{6}$$

$$\overline{Q_{DG}} = [Q_{G1}, Q_{G2}, ..., Q_{G_i}]_{1\times N_G}, \forall i = 1,..., N_G \tag{7}$$

$$\overline{Q_{svc}} = [Q_{svc1}, Q_{svc2}, ..., Q_{svc_i}]_{1\times N_{svc}}, \forall i = 1,..., N_{svc} \tag{8}$$

$$N = N_t + N_c + N_G + N_{svc} \tag{9}$$

Subject to:

$$V_i^{Min} < V_i < V_i^{Max} \tag{10}$$

$$t_{\min} < t < t_{\max} \tag{11}$$

$$Q_{svc}^{Min} < Q_{svc} < Q_{svc}^{Max} \tag{12}$$

$$P_{DG}^{Min} < P_{DG} < P_{DG}^{Max} \tag{13}$$

$$\left| I_{ij} \right| \le \left| I_{ij} \right|^{\max} \tag{14}$$

$$PF^{Min} < PF < PF^{Max} \tag{15}$$

where V_i^{ref} is the reference voltage of bus i, V_i is the voltage of bus i, R_i is resistance of branch i, I_i is the current of branch i, Pr_h is hourly cost of energy, P_s is generated power in network, P_{DG} is generated power by DG and C_{DG} is generation cost of DG. The proposed model is subjected to the below constraints. Also, V_i^{Min}, V_i^{Max} are minimum and maximum voltage, $t_{\min}, t_{\max}$ are lower and upper limit of tap status. Eq. (12) presents the constraint of injection or absorption of reactive power of static compensators. Eq. (13) describes the constraint of active power generation of DGs. Eq. (14) is thermal constraint of lines and Eq. (15) is also the power factor constraint.

IV. SOLVING APPROACH: HARMONY SEARCH ALGORITHM

As earlier noted, many algorithms for solving engineering optimization problems are presented, most of which are based on linear and non–linear programming methods. Numerical optimization algorithms in finding an optimal global solution in an ideal and simple model are useful. But in the face of real and complex optimization problems have limitations and are not efficient enough. Computational drawbacks in engineering optimization problems, researchers will make use of meta−heuristic algorithms [10]. The harmony search algorithm is a meta–heuristic algorithm developed recently by "GEEM *et al*" [10] based on the improvisation of harmony in the music composition. This algorithm has been inspired by music phenomenon. In the process of playing music, a wonderful state of harmony search is estimated to be based on standards of aesthetics. So that instrumentalists experimentally and step by step play their instruments in order to better sound and higher harmonies. This process is similar to the optimization process that optimal global solution can be searched by evaluating the objective function (i.e., fitness function). This is main similarity between music phenomenon and optimization in harmony search algorithm. In this algorithm solution vector is called "HARMONY". In other words, every harmony is a vector that their components are values assigned to decision variables of a problem. If the problem has "N" variables, harmony or solution vector also will have "N" components [11-12]. To implement harmony search algorithm based on the music phenomenon should be established correspondence between the components in Table 2. The all optimization process is represented with a flowchart in Fig. 1 [25]. The harmony search algorithm for every considered optimization problem following a determined procedure in five phases as follows [13]:

- Phase 1− Commence of the problem and its parameters (i.e., input requirement data);
- Phase 2− Initialize the harmony memory;
- Phase 3− Improvise a new harmony (i.e., improvisation in music phenomenon);
- Phase 4− Update the harmony memory;
- Phase 5− Requirement of stopping (i.e., repeat of phases 3 and 4 when the stopping criterion is satisfied).

A. *Definition of the Problem and its Parameters*

In the first phase, the optimization problem is defined initially as minimize $\{ f(x) \mid x \in X \}$ subject to constraints which X is the set of possible range of the decision variables and x is the set of decision variables.

Table 2. Correspondence table music phenomenon and harmony search algorithm

NO.	Harmony search algorithm	Music phenomenon
1	Decision variables	Music instruments
2	Range of variables	Range of notes
3	Solution vector	Harmony
4	Objective function	Standards of aesthetics
5	Iteration	Practice
6	Harmony memory	Experience

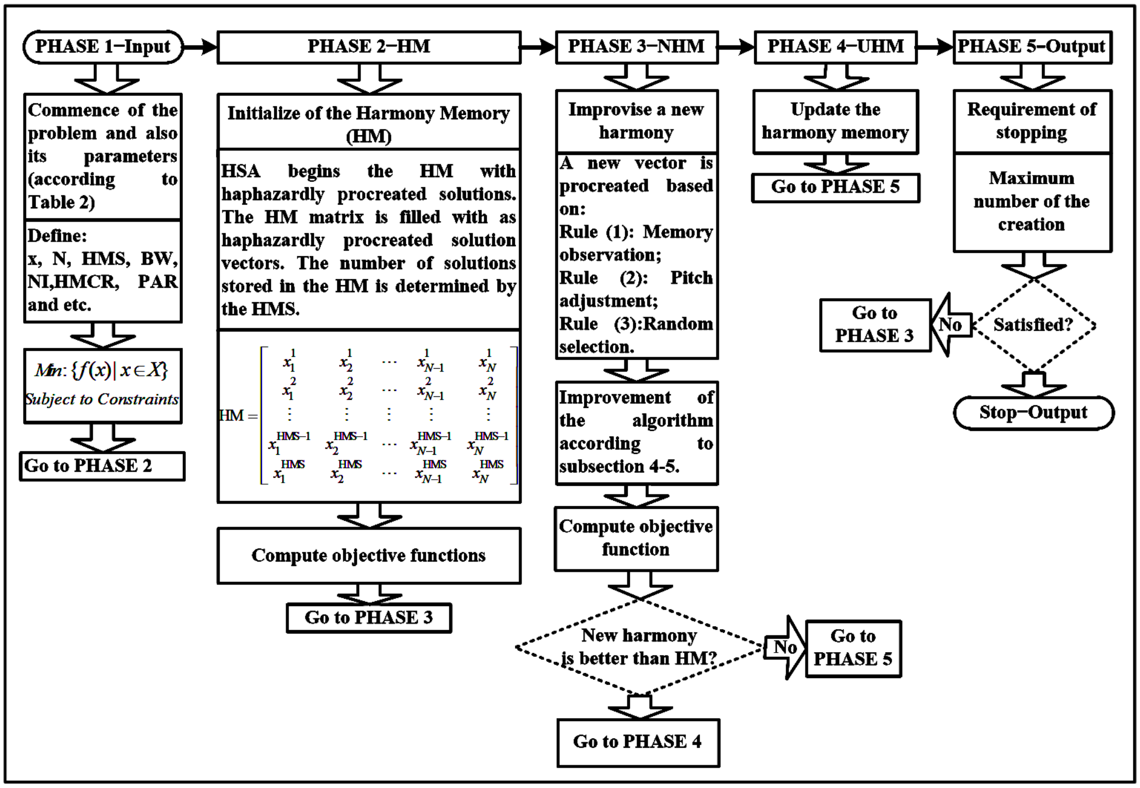

Fig. 1. Optimization procedure of the improved harmony search algorithm.

Table 3. The HSA parameters and its abbreviation

NO.	HSA parameters	Abbreviation
1	Harmony Memory (i.e., sets of decision variables)	HM
2	Harmony Memory Size (i.e., number of solution vector)	HMS
3	Harmony Memory Considering Rate	HMCR
4	Pitch Adjusting Rate	PAR
5	Number of decision variables	N
6	Number of Improvisations	NI
7	Band Width	BW

Also, the parameters of the HSA can be varying amounts in any optimization problem are classified according to Table 3. As earlier noted, these parameters as input data define and choose for different problems in the first phase. It should be mentioned that the HM is similar to the "GENETIC POOL" in the GA [12]. Here, HMCR and PAR are parameters that are used to improve the solution vector.

B. Initialize of the Harmony Memory

In the HM matrix are saved the sets of decision variables. In initialization step, the HM matrix is filled with haphazardly procreated solution vectors with a uniform distributed and represented as follows in Equation (16).

$$HM = \begin{bmatrix} x_1^1 & x_2^1 & \cdots & x_{N-1}^1 & x_N^1 \\ x_1^2 & x_2^2 & \cdots & x_{N-1}^2 & x_N^2 \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ x_1^{HMS-1} & x_2^{HMS-1} & \cdots & x_{N-1}^{HMS-1} & x_N^{HMS-1} \\ x_1^{HMS} & x_2^{HMS} & \cdots & x_{N-1}^{HMS} & x_N^{HMS} \end{bmatrix} \quad (16)$$

It should be noted, the decision–making variables in the proposed real-time control is according to the Equation (4).

C. Improvise the New Harmony from the HM

Improvisation is a process of creating a new harmony from the existent memory. A new harmony vector as $X' = (x_1', x_2', \ldots x_N')$ is generated according to three rules: memory observation, pitch adjustment and random selection. In this step, the value of the first decision variable is selected from one of the harmony between x_1^1 to x_1^{HMS}. The other decision variables in the HM are selected in the like method with the probability of the HMCR which it varies between 0–1 based on Equation (17).

$$x_i' = \begin{cases} x_i' \in \left\{ x_i^1, x_i^2, \ldots, x_i^{HMS} \right\}; \textit{with prob (HMCR)} \\ x_i' \in X_i; \textit{with prob ([1 - HMCR])} \end{cases} \quad (17)$$

The HMCR is the rate of selecting a variable from the historical data in the HM and also (1–HMCR) is the rate of haphazardly selecting one value from the feasible range of values. Afterward, all the components are pitch adjusted using the PAR. The decision of pitch adjustment is YES with the probability PAR and NO with the probability (1–PAR) according to Equation (18). In this Equation, "$rand$" is a uniform random number between 0 and 1.

$$x_i^{'} = \begin{cases} x_i^{'} + rand \times BW; \text{with prob } (PAR) \\ x_i^{'}; \text{with prob } ([1-PAR]) \end{cases} \quad (18)$$

D.Fuzzy sets theory (Evaluation of optimum solution)

Since definition of solution set, attaining a flexible solution is appropriate that shows a trade–off between different objectives [15]. There are many methods for choosing a reconciliation solution among solutions set, a fuzzy method is of great interest because of its easiness and conformity to human logic. The fuzzy sets are clarified by membership functions which show the degree of membership in a fuzzy set using values from 0 to 1 [16]. In fuzzy method, a strictly monotonically decreasing and continuous membership function is assigned to each objective. The value of the membership function indicates to what extend a solution is satisfying the objective f_q . There are some types of strictly monotonically decreasing and continuous functions which can be used as membership functions. In this paper, the linear type has been utilized for all objectives as follows:

$$\mu_{f_q}(\bar{X}) = \begin{cases} 0 & ; f_q(\bar{X}) \succ f_q^{\max} \\ \dfrac{f_q^{\max} - f_q(\bar{X})}{f_q^{\max} - f_q^{\min}} & ; f_q^{\min} \le f_q(\bar{X}) \le f_q^{\max} \\ 1 & ; f_q(\bar{X}) \prec f_q^{\min} \end{cases} \quad (19)$$

Fig. 2 illustrates the graph of this membership function. To determine the membership functions of the criteria, at first, values of each criterion is calculated in different states during the planning horizon. So, the individual maximum and minimum values of each objective would be calculable.

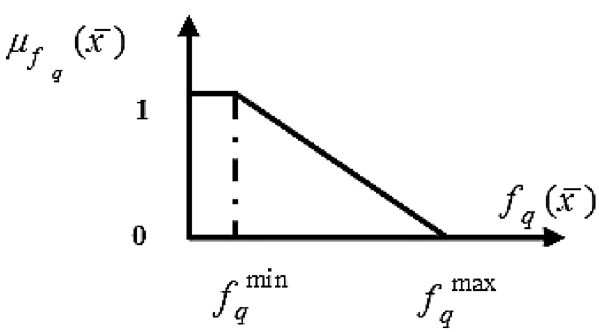

Fig. 2. Linear type membership function.

By taking account of the individual minimum and maximum values of each objective function, the membership function $\mu_{f_q}(\bar{X})$ for each objective function can be determined in a subjective manner. Then, in order to solve the proposed model as a multi–objective optimization problem with Q objective functions, the final solution is selected based on Equation (20).

$$\max\left\{ \min \left\{ \mu_{f_q}(\bar{X}) \right\} \right\} \quad ; q = 1, 2, \ldots Q \quad (20)$$

V.SIMULATION AND CASE STUDIES

In this paper, a real-world distribution network which is part of Tehran distribution network is considered as a test system. Single line diagram of this network in the presence of DGs and other devices is shown in Fig. 3. In this network, the capacity of installed capacitors is 200 kVAR, and capacitors can be in the on-off state. OLTC and voltage regulators taps increase in range of 0.95 -1.05 with 0.01 steps. Also, there are two 1 MW wind power plant and one 500KW solar power station that respectively has been installed in 7,9 and 10 buses. In addition, the impedance of overhead lines is 0.362+j0.348 (Ohm/km) and the capacity of SVSs is 400 kVAR and has been installed in 10 ,12 buses. All numeric requirements of the proposed model are tabulated in Table 4. The presented approach is applied in Matlab platform and tested on a PC with a 2.26 GHz processor. Mean execution time for each hour of day with the SSE is less than eight seconds, which is admissible time for real time control.

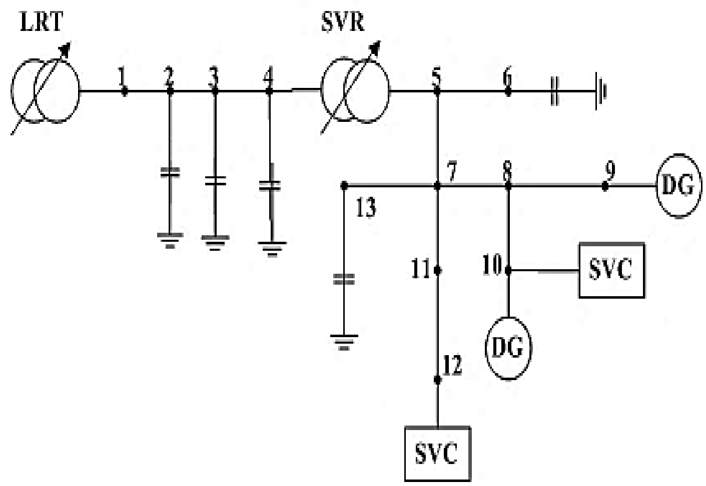

Fig.3. distribution network under study.

Table 4. All numeric requirement of the proposed model

No.	Parameters	Numeric value
1	V_i^{Min}	0.95
2	V_i^{Max}	1.05
3	$t_{\min}$	0.9
4	$t_{\max}$	1.1
5	Q_{SVC}^{Max}	400
6	Q_{SVC}^{Min}	-100
7	P_{DG}^{Max}	700
8	P_{DG}^{Min}	-100
9	PF^{Max}	1
10	PF^{Max}	0.1

As stated earlier, in this paper, estimated hourly load has been used for real time control of voltage and reactive power. in addition, three cases are defined so as to study the feasibility and effectiveness of the proposed method. In the first case, no control devices are considered. In the second case, all system devices (SVC, SHC, OLTC and VR) are taken into account except DGs. In the third case, all system devices (RES, SVC, SHC, OLTC and VR) are regarded.

Fig. 4 depicts the voltage profile at the period of the low load. In this time load value is 56% peak load and price of energy is 0.0341 [$/kwh]. This Fig. shows in first case because there is no control device, buses voltage of 5 to 13 has violated of minimum standard voltage (0.95 p.u.).

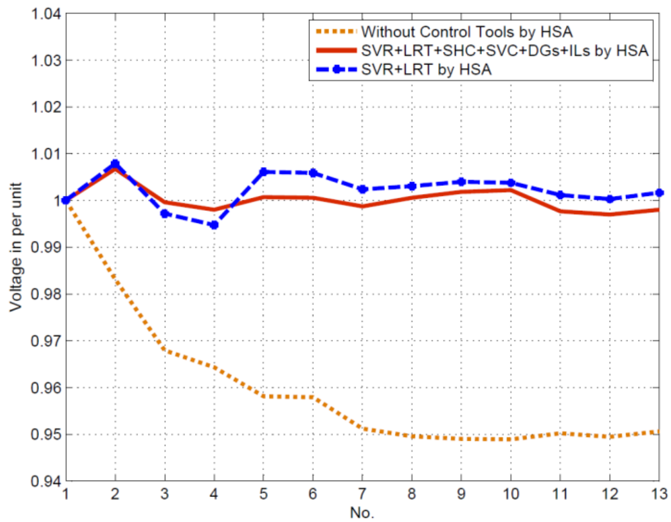

Fig.4. Voltage profile at period of low load.

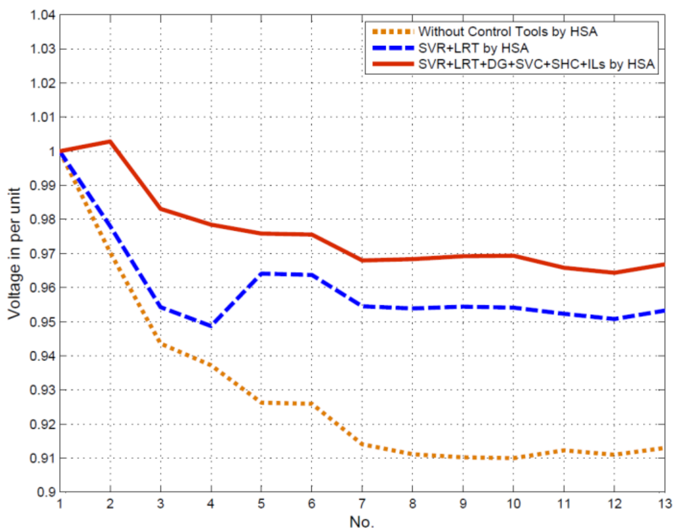

Fig.5. Voltage profile at period of peak load.

In the second case, the buses voltage has not violated of standard voltage. But violation is more than the third scenario that DGs are connected to network. Fig. 5 illustrates the voltage profile at the period of the peak load. Load in this time equals to pick load and price of energy is 0.0498 [$/Kwh]. In the first case has violated of minimum standard voltage. In the second and third cases buses voltage are standard. In this time in the third case that DGs are connected to the network, voltage increasing between buses 4, 5 is because of changing tap position to high steps in installed regulator between two buses. In the third scenario voltage profile is more flat than the second scenario. Fig. 6 demonstrates the voltage profile at period of the medium load. In this time load is 74% of pick load and price of energy is 0.0449 [$/kwh] . In the first case buses voltage of 3 to 13 has violated the standard. In the second case buses voltage is standard. Voltage increasing between buses 4, 5 is due to changing tap position to high steps in installed regulator between two buses. In the third case voltage profile is more flat than the second scenario. Table 3 tabulates objective functions values in three cases. When DGs have been connected to network, all of objective functions values such as buses voltage violations, losses and cost is less than other scenarios.

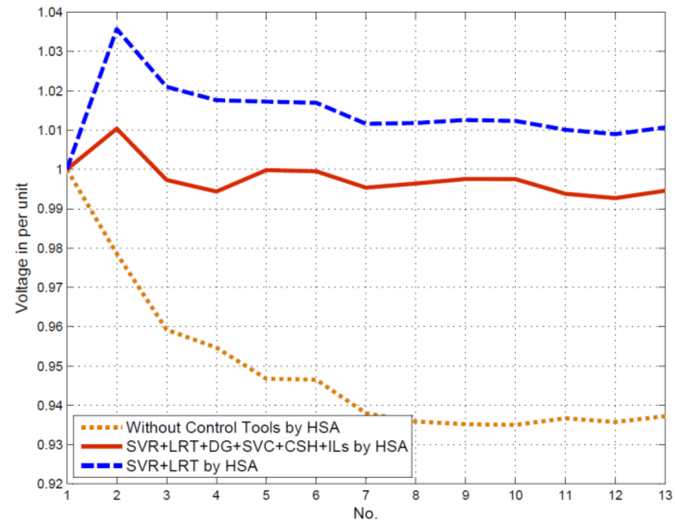

Fig.6. Voltage profile at period of medium load.

In addition, the obtained results by proposed HSA under third case, namely, RES, SVC, SHC, OLTC and VR, are compared with the calculated results by PSO and GA under related case in Table 4.

Table 3. All numeric requirement of the proposed model

Case NO.	Low load			Medium load			Peak load		
	F1 (pu)	F2 (kw)	F3 ($)	F1 (pu)	F2 (kw)	F3 ($)	F1 (pu)	F2 (kw)	F3 ($)
First case	0.64	296	181.5	0.58	482	288	1.0	995	465
Second case	0.11	191	199	0.25	304.8	261	0.10	612.1	497
Third case	0.027	58	101.5	0.061	132	194	0.09	379	366

Table 4. Comparison obtained results by HSA, PSO and GA

Third case	Low load			Medium load			Peak load		
	F1 (pu)	F2 (kw)	F3 ($)	F1 (pu)	F2 (kw)	F3 ($)	F1 (pu)	F2 (kw)	F3 ($)
HSA	0.027	58	101.5	0.061	132	194	0.09	379	366
PSO	0.03	69	143.7	0.07	147	258	0.1	438	408
GA	0.08	73	159.4	0.1	161	279	0.25	461	452

As set out in Table 4, the newly proposed method by using HSA leads to more efficient results than PSO and GA [16]. As a result, it can be concluded that the newly proposed method by HSA is more adequate and profitable than the method of presented in Ref. [16] for solving the proposed problem. In addition, convergence curves of the HSA, the PSO and the GA has been demonstrated in Fig. 7. According to the this Fig., it can be seen that the convergence curve of the proposed HSA is optimized better, faster and precise than that of the proposed

PSO and the GA. Also, loss fluctuations at 24 hours under three considered cases are presented in Fig. 8. As seen this Fig., network loss by considering DG is less than two other cases. Also, when control tools are ignored in the network, the loss is increasing.

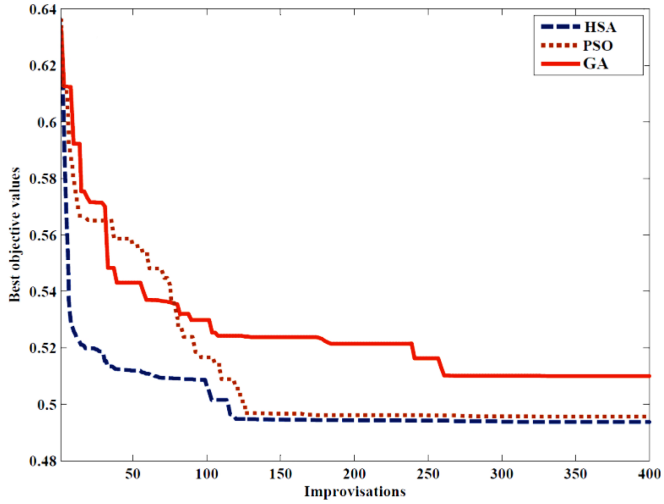

Fig. 7. Convergence curve for the proposed HSA, PSO and GA.

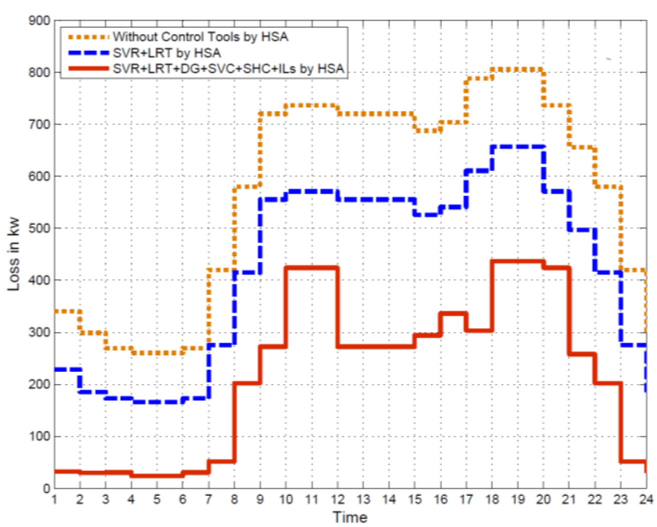

Fig.8. Loss fluctuations at 24 hours.

VI. CONCLUSION

In this paper, a new approach discussed to real-time control of Volt & var in the distribution network.

The newly proposed method is based on the control tools of network and DGs, which it leads to changing operation method of the network. Also, the proposed method is modeled by a mixed-integer, non-linear and multi-objective problem to apply real-time control policies. Accordingly, a multi-objective harmony search algorithm is used for solved the applied real-time problem and followed by a fuzzy method.

The voltage deviation, losses, and cost are considered objective in the proposed real-time control process. The proposed model is successfully applied to the real-world distribution network. The obtained results from case studies revealed that regarding DGs in the real-time process can lead to less network losses and cost in comparison with ignoring DGs and other control tools.

In addition, it was observed that the obtained results from the newly proposed method, in accordance with the harmony search algorithm, were more effective than the results from the particle swarm optimization and genetic algorithm. Since the harmony search algorithm has higher accuracy and speed in comparison with other employed algorithms.

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