Application of TLBO Algorithm for Multi-Objective Optimization of DVR Controller

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ABSTRACT

Access to high quality power is one of the goals in electric power networks. Any perturbation to power distribution systems results in voltage disturbances. Thus, in order to mitigate these disturbances on sensitive consumers, various measures and devices could be implemented. In this paper, Dynamic voltage restorer (DVR) is used to handle voltage variations of sensitive loads. In order to regulate PI controller's coefficients, a combination of multi-objective teaching-learning-based optimization (TLBO) and fuzzy membership function is employed to simultaneously optimize voltage THD and sag in sensitive loads. Effectiveness of the hybrid method is validated by simulations.

Keywords: *power quality, DVR, sensitive load, teaching-learning-based optimization, multi-objective optimization, fuzzy membership function*

1. INTRODUCTION

With the ever-increasing growth of sensitive industrial and residential consumers, sustainable and high quality access to electric power has also been increased. In competitive industrial medium, with the use of power electronic devices, computer processors and nonlinear loads, any interruption or variations beyond standards of power quality will lead to economic losses. The economic losses can be represented in several frameworks, including loss of competition opportunities of producer, efficiency reduction and production cost rise, reduced quality, decreased lifetime of devices, increased maintenance cost, interrupted power, and power loss. Hence, access to a high-quality power is very effective in capital reduction for a manufacturing firm [1].

Perturbation to electric distribution system leads to destructive disturbances in distribution system such as power interruption, voltage sag, voltage swell, and flicker. Voltage sag is among the most important perturbations that is defined in IEEE standard as: sudden drop of voltage magnitude by 10-90% within 0.5 cycle to 1 minute [2] that is due to various natural phenomena such as asymmetrical faults in the network and electromagnetic events, including starting and inrush currents.

In order to mitigate the abovementioned influences on sensitive consumers in distribution system, custom power devices are highly considered by experts in this field. One of these devices is dynamic voltage restorer (DVR) that is able to cope with voltage sag and voltage swell effects in sensitive loads. In the simplest form, this compensator is composed of the following components: energy storage, voltage source inverter and coupling transformer. Once voltage sag is detected in a feeder terminating in sensitive load, DVR compensates voltage reduction by injecting sufficient voltage through coupling transformer in series with sensitive consumer.

In order to operate appropriately, different control strategies such as predictive control [3], sliding-mode control [4], and robust control [5] are employed for inserted voltage control.

In this paper, a novel method based on teaching-learning-based optimization (TLBO) algorithm is proposed to solve optimum determination of PI controller parameters. This algorithm is inspired by an interaction between a teacher and students in a classroom. In addition, a multi-objective optimization with fuzzy membership function is used to improve consumer voltage sag and THD indices. In order to show the effectiveness of the proposed algorithm, DVR performance is examined in the presence of various faults and the obtained results of the proposed controller is compared with those of single-objective method. In Section II, DVR operation is introduced. And Section III details multi-objective function optimization with fuzzy membership function. In Section IV, TLBO algorithm is analyzed. And finally, simulations along with the obtained results are provided.

2. DVR; Structure and Description

DVR is one of the custom power devices connected in series into power distribution networks. DVR fixes load voltage amplitude by inserting three-phase voltages during disturbances in power system and along with controlling voltage amplitude, phase angle, and frequency of the supplied voltage would be regulated. Thus, the DVR operation is based on inserting required voltage in the event of voltage sag. In general, DVR performance may be divided into two modes: standby mode and injection mode [6]. In the first mode, in the case of occurring (or not occurring) a short circuit, a small voltage is inserted to compensate voltage drop caused by transformer reactance losses. In the second mode, once voltage sag is detected, DVR inserts a voltage into sensitive load.

DVR model comprises of five components, as shown in Fig. 1.

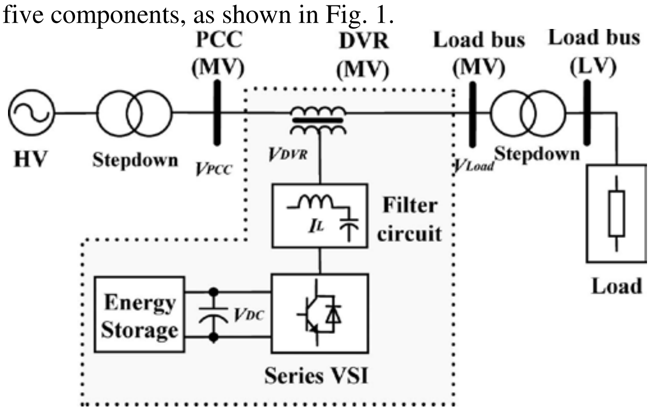

Fig. 1. DVR circuit in power system

1) Series-connected transformer: its primary winding is connected to inverter bridge while the secondary winding is connected to the distribution network and sensitive load.
2) Voltage source inverter: this inverter bridge is connected to primary winding of the insertion transformer. An energy storage device is considered for inverter bridge. These inverters are equipped with self-commutation IGBT switches and parallel diodes. Pulse with modulation (PWM) is used to control switch operation.
3) Energy storage element: energy storing sources such as batteries, capacitor banks, SMES, and flywheels are utilized in DVR to provide required voltage level and reactive power to compensate voltage sag [7].
4) Passive filter: it is placed in high voltage-side of inverter to eliminate harmonics produced by switching.
5) Control system: this control system's logic is based on detection of voltage drop and providing proper switching strategy of the inverter.

Control system makes use of abc-dq transformation to obtain v_d and v_q. In normal mode, these voltages are: v_d=1, v_q=0. However, in the event of faults, they may change [8]. Thus, by comparing these quantities with those of reference ones (v_d and v_q), putting error signal to PI controller can control the variations.

3. Multi-objective optimization with membership function

In order to regulate PI controller's coefficients, a combination of multi-objective teaching-learning-based optimization (TLBO) and fuzzy membership function is employed to simultaneously optimize voltage THD and sag in sensitive loads.

So far, various approaches have been proposed to solve multi-objective optimization problems. Most of multi-objective optimization problems have no consistent objectives (with similar search space dimension), thus, particular methods should be employed to solve these types of problems or make the objectives consistent. One of these methods is to define each objective of the problem in membership function form within fuzzy sets and then combine them with appropriate weighting factors as a single fuzzy objective function [9] and [10]. If this method is used to optimize voltage THD and sag in a sensitive load, objective function in (1) can be used:

$$F=w_1.\mu_T+w_2.\mu_D \qquad \text{Maximize} \qquad (1)$$

where μ_T is the membership function quantity of sensitive load voltage THD, μ_D is the membership function quantity of sensitive load voltage sag, w_1 and w_2 are weighting factors related to each objectives of the problem.

The main reason behind implementation of this method for optimization of two objectives (i.e., sensitive load voltage THD and sag) is that these objectives are not reversed growth objectives. In other words, voltage THD reduction does not lead to increased voltage sag and vice versa.

This problem can be solved by appropriately determining membership functions and the weighting factors related to each objective of the problem. Due to the importance and influence of weighting factors on the system, they are selected in a way that their sum is equal to1. Fuzzy membership function for optimization goals that represents objective optimality within [0, 1] may have various quantities considering the problem type [11]. In the following, proposed membership functions for each objective are provided:

1.1. Voltage sag membership function

With regard to voltage sag, it is tried to minimize the difference between base value of bus voltage and real value of bus voltage caused by power system faults. This voltage deviation can be obtained by (2):

$$D = \max|v_b - v_l| \tag{2}$$

where v_b is base voltage of bus with sensitive load and v_l is sensitive load voltage amplitude. If maximum voltage sag value of a bus of interest decreases, more optimality is dedicated to it. And, if voltage deviation increases, less optimality is obtained. Relationships and shape of membership function related to this objective are expressed in (2) and (3), respectively:

$$\mu_D = \begin{cases} \frac{D_{max} - D}{D_{max} - D_{min}} & \text{for } D_{min} \le D \le D_{max} \\ 1 & \text{for } D \le D_{min} \\ 0 & \text{for } D \ge D_{max} \end{cases} \tag{3}$$

According to the IEEE-519 standard, acceptable voltage for each bus maybe within 0.95-1.05 p.u. here, following values are considered: Dmin-0 and Dmax=0.05.

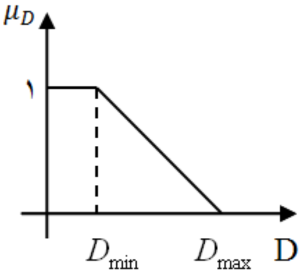

Fig. 2. Voltage sag membership function

1.2. Membership function of sensitive load's voltage harmonics

A sensitive load may be sensitive to voltage harmonics, and its voltage harmonics creates inappropriate disturbances in it. Thus, harmonics minimization is a valuable objective. Load harmonics index for a load is the extracted THD which its membership function is expressed by (4) and depicted by Fig. 3. Based on the mentioned standard, the acceptable THD is 5%. Therefore, in this paper, Tmin=0 and Tmax=0.05.

$$\mu_T = \begin{cases} \frac{T_{max} - T}{T_{max} - T_{min}} & \text{for } T_{min} \le T \le T_{max} \\ 1 & \text{for } T \le T_{min} \\ 0 & \text{for } T \ge T_{max} \end{cases} \tag{4}$$

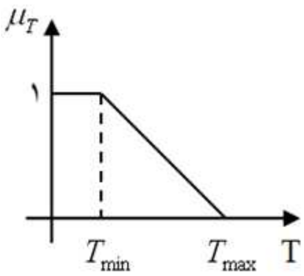

Fig. 3. THD membership function

4. Teaching-learning-based optimization (TLBO) algorithm

Teaching-learning-based optimization (TLBO) algorithm was introduced by Rao in 2012 [12]. TLBO algorithm is proposed based on learning and teaching principles in a classroom. This algorithm addresses optimization by learning and teaching. Teacher plays a key role in class and can teach students and elevate the average level of the class.

TLBO algorithm is employed especially on continuous problems. However, it can be also used for discrete and binary problems.

TLBO algorithm operates based on the impact of a teacher on students' output in a class. And, in a class, teacher is a person with the best value and can share its knowledge throughout the class. In TLBO algorithm, two optimization phases exist [13-15].

Teacher phase

Consider that M_i and T_i are the average and teacher in *i*th iteration. T_i tries to increase M_i average, creating new mean 'M_{new}.' A solution is updated with respect to the difference between current mean and new mean [12]:

$$Difference\_Mean_i = r_i(Mean_{new} - T_F M_i) \tag{5}$$

where T_F is the teaching factor that decides to change mean value and r_i is a random number between [0, 1]. Teaching factor is produced randomly during the algorithm's execution in [1, 2] in which 1 is related to knowledge increase while 2 is related to knowledge transfer. T_F value is calculated by:

$$T_F=round[1+rand(0,1)\{2-1\}] \tag{6}$$

Based on the difference and mean, solutions are updated:

$$X_{new,i} = X_{old,i} + Difference_{Mean_j} \tag{7}$$

Student phase

In this phase, students can increase their knowledge via random interaction among them. Students can learn new things from other students with higher knowledge. Learning in this stage in each iteration *i* is performed between two different students 'X_i' and 'X_j' by:

$$X_{new,i} = X_{old,i} + r_j(X_i - X_j), \quad \text{Iff}(X_i) < f(X_j)$$
$$X_{new,i} = X_{old,i} + r_j(X_j - X_i), \quad \text{Iff}(X_j) < f(X_i) \tag{8-9}$$

TLBO algorithm can be summarized as:

Step 1: determination of optimization problem and initialization of parameters;
Step 2: initialization of population by random generation and their evaluation;
Step 3: selection of the best learner in each course as a teacher and calculation of students' mean in each course;
Step 4: evaluation of the difference between the current result and the best global mean;
Step 5: students' knowledge update by teacher knowledge;
Step 6: students' knowledge update by their knowledge (among themselves);
Step 7: if termination criterion is not met, go to the Step 3.

When a termination criterion is met, the final solution is considered as the best one.

5. Simulations and Results

The case network has two buses one of which supplies a sensitive load. This simple network is depicted in Fig. 4 and its parameters are provided in Table (I).

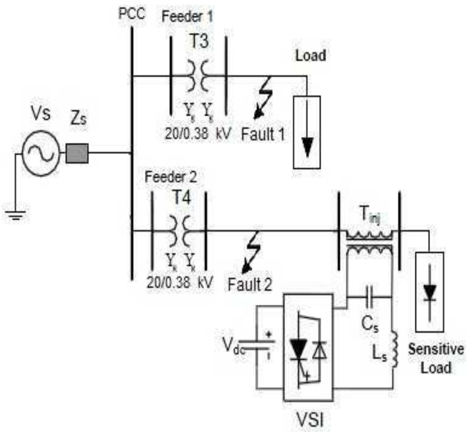

Fig 4. Case network

Table I. network parameters [16-18]

Parameters	Amount
Network frequency Supply voltage	Fn=50 (Hz) Vs=22500 (v)
Active and reactive power of sensitive load	P=2000 (w) Ql=40 (var) QC=10 (var)
Active and reactive power of non-sensitive load	P=2500 (w) Ql=40 (var)
Nominal power and turn ratio of the network transformers	Pn=3200 (w) 20000/380
Impedances of the two transformer in the network	Rl=0.0003 (p.u) Xl=0.001 (p.u) Rm=Xm=500 (p.u)
Nominal power and turn ratio of the insertion transformers	Pn=1500 (w) 100/1000
Impedance of insertion transformer	Rl=0.00001 (p.u) Xl=0.0003 (p.u) Rm=Xm=500 (p.u)
DVR's switching frequency	FS=10000 (Hz)
Energy storage device voltage	VDC=200 (v)
Impedances related to series and parallel impedance	RS=0.2 (ohm) LS=6 (mH) RP=0.2 (ohm) CP=20 (μF)

In a distribution system, the more a fault occurs near a point of interest, the higher the voltage drop will be on that point. Thus, in order to model much critical conditions, two faults are used. One of the faults is placed after series insertion transformer and the other is near non-sensitive load. The first short circuit fault occurs on phase B; while the second short circuit fault occurs on phase A and B and their characteristics are provided in Table II [19-21].

Table II. Characteristics of current faults in the network

Eart h resistance	Fau lts resistance	F ault time	P hases of faults	
0.1	4.6	[0.10, 0.14]	B	ault 1
0.1	4.6	[0.005, 0.065]	A, B	ault 2

This problem is first solved as a single-objective to optimize voltage drop caused by network faults. Then, the TLBO algorithm is used to solve the problem with iteration number and population of 50 and 20, respectively. The results obtained reveal voltage drop improvement in sensitive loads. However, sensitive load is not appropriate in terms of THD (Fig. 5 and Table. III). Therefore, it was attempted to use multi-objective algorithms. In Fig. 5, PCC voltage, sensitive load voltage, DVR insertion voltage, as well as differential signal between base load voltage and voltage caused by network faults are depicted during overall program execution.

Firstly, each problem objective is transformed into a fuzzy membership function to get a solvable optimization problem. In solving this problem, all objectives have similar importance. Thus, $w_2=w_1=0.5$. This problem is solved with 40 iterations and 20 individuals. In simulations, PCC voltage, sensitive load voltage, DVR insertion voltage, as well as differential signal between base load voltage and voltage caused by network faults are depicted in Fig. 6 during overall program execution.

THD signal improvement and differential signal between base load voltage and voltage caused by network faults are examined thoroughly. As seen, IEEE-519 standard requirements are observed during total simulation time. Table III details performance improvement in access to observable objectives. Fig.7. shows Convergence curves of TLBO, PSO and GA algorithms.

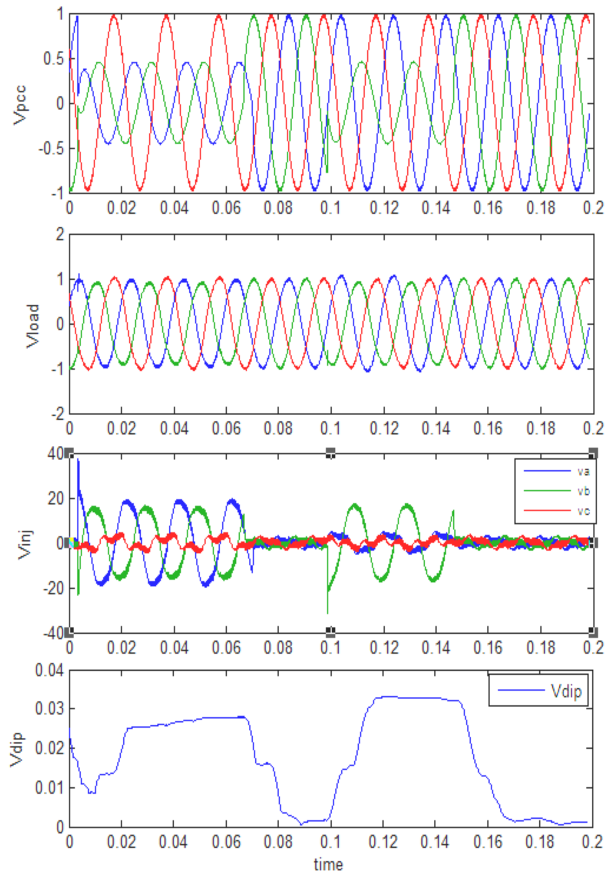

Fig. 5. PCC voltage, sensitive load voltage, insertion voltage and differential signal between base load voltage and sensitive load voltage in single objective optimization

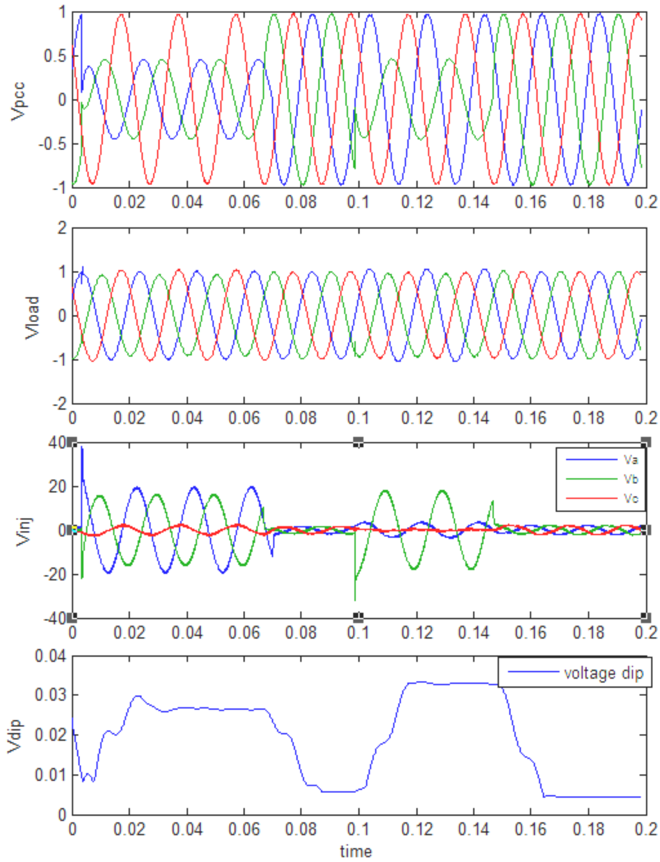

Fig. 6. PCC voltage, sensitive load voltage, insertion voltage and differential signal between base load voltage and sensitive load voltage in multi-objective optimization

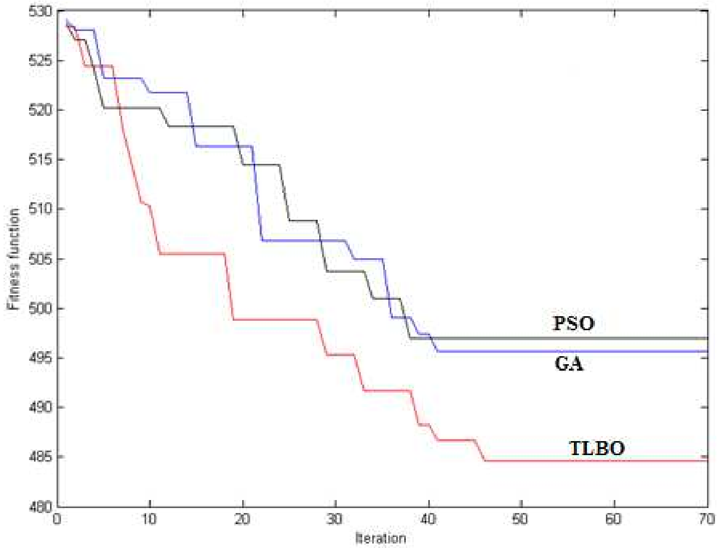

Fig. 7. Convergence curves of TLBO, PSO and GA algorithms

Table III. Results of voltage sag and THD indices in both single and multi-objective method

		Voltage sag average		THD (%)	
Controllers	***tates***	***value***	***Improve (%)***	***alue***	***Improve (%)***
Classical PI		0.0205	-	4.87	-
		0.0273	-	.94	-
GA		0.0177	13.66	.61	87.47
		0.0203	25.64	.63	84.01
PSO		0.0198	3.41	.61	87.47
		0.0215	21.24	.65	83.5
Single objective TLBO		0.0177	13.66	.46	70.02
		0.0203	25.64	.59	59.64
Multi-objective TLBO		0.0131	36.09	.91	81.31
		0.0178	34.79	.96	75.63

6. Conclusion

According to the results obtained by applying the proposed algorithm to the test network, it can be said that this algorithm is a good approach for improving power quality for customers. As it is clear, due to dynamic behaviors of power system under normal and fault conditions, it is difficult to have a good model. So, to achieve fast and accurate performance of compensators, intelligent control algorithms should be used. The proposed controller has shown a very good performance under test cases. The TLBO controller mainly was designed to have a better performance in voltage drop of sensitive load, but it was shown that by improving that, a better compensation in THD index can also be achieved. Designing this controller does not have much complexity. It should be noted that the good performance of proposed approach is obtained without using specific additional equipment which can make it more cost-effective.

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