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Optimal Coordinated Control of OLTCs using Taguchi Method to Enhance Voltage Stability of Power Systems

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Abstract

On-load tap changer (OLTC) plays a significant role to regulate the voltage of the power system. Although some time, secondary voltage of an OLTC is pulled down when tappings are raised to restore the voltage level. This situation may finally lead to voltage collapse. To address this problem, the behavior of tap setting of OLTCs is investigated, and critical transformer and its allowed range of tap settings is identified in the paper. This paper also proposes a Taguchi based method to find optimal tap settings of OLTCs including critical transformer to improve the voltage stability margin and decrease the real power loss of the system. The proposed method is tested on IEEE 30-bus system to validate its applicability.

Keywords: L-index; critical transformer; voltage stability; tappings

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Nomenclature

P_L	Active power loss;
G_x	Conductance of line at xth bus;
B	Susceptance of Line;
V_i	Voltage magnitude at i^{th} bus;
V_j	Voltage magnitude at j^{th} bus;
n	Total number of buses;
P_G	Real power at generator end;
P_D	Real power at demand end;

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Q_G	Reactive power at generator end;
Q_D	Real power at demand end;
V_{max}	Maximum allowable bus voltage;
V_{min}	Minimum allowable bus voltage;
T_{max}	Maximum allowable tap changer limit;
T_{min}	Minimum allowable tap changer limit;
T	Number of trials in each experiment;
N	Number of transformers
θ_{ij}	Impedance angle of line ij;

1. Introduction

Present power systems are operated under stressed condition. A slight disturbance at this stage results in reduction in EHV level voltages which is reflected finally in the distribution system network. The action of on-load tap changer (OLTC) helps to restore the voltage at previous levels. With each tap changing operation, the line current would increase, thereby increasing the reactive power loss of the system. As a result the reactive power output of the generators increases gradually and generators may reach to their reactive power capability limit. Beyond that generators loses their capability to support the system voltages, thereby causing the problem of voltage instability. Therefore, operation of OLTCs is critical for voltage stability and line losses of the system [1]-[2].

Numerous studies have been carried out in this area. Liu *et al.* [3] remodeled the voltage collapse phenomenon by co-relating non-linear dynamic models of impedance loads, OLTCs and de-coupled reactive power-voltage relations. Abe *et al.* [4] investigated the effect of dynamic tap changer on voltage stability using eigenvalue analysis. Medinac *et al.* [5] proposed an approach to model, analyze, and design of slow distributed voltage control schemes. In [3], a stability region around the stable equilibrium is derived through a nonlinear analysis of the continuous model. Ohtsuki *et al.* [6] discussed the reverse action that the secondary voltage of a transformer is pulled down when the tap position of on-load tap changer is raised to increase the secondary voltage.

Furthermore, several algorithms have been presented to obtain the optimal settings of tap changers. Bansilal *et al.* [7] proposed an expert system for alleviating the voltage violations by applying switchable shunt reactive compensation and transformer tap settings. Devaraj *et al.* [8] presented an improved Genetic Algorithm (GA) approach for voltage stability enhancement by optimizing OLTC tap settings, generator excitation, and reactive power compensation provided by capacitor banks. Yang *et al.* [9] used Hybrid Differential Evolution (HDE) technique to determine the tap settings of OLTC transformers to improve the voltage stability of the system.

Various established Artificial intelligence (AI) techniques discussed above use more complicated search methods for optimization. These methods use iterative trial and error progress with large data sets which are comparatively time-consuming. Conversely, the Taguchi method (TM) is an effective tuning method which is well defined, systematic and simple in steps. Moreover, TM chooses a combination of factors (the factors which is to be altered) that are robust against the behavior of the system changes. Taguchi works on orthogonal array (OA) and OA gives all possible combinations, such that the best solution lies within the combinations. Taguchi method (TM) has been applied successfully to optimization problems in power systems [10]-[11]. Therefore, in this viewpoint TM is quite superior to other AI methods. Tap positions of OLTC is discrete in nature. TM is better than other established AI techniques when variables are discrete in nature. TM has not been considered so far to find the optimal setting of OLTCs in the system so as to minimize active power loss and to improve the voltage stability of the system.

Considering the merits of Taguchi method, this paper proposes the application of Taguchi method to find the coordinated tap settings of OLTCs so as to improve the voltage profile and voltage stability margin, and to decrease real power loss of the system. Another contribution of the paper is to propose a method to identify the critical OLTC and its possible tap settings so as to prevent voltage instability.

The proposed methodology is tested on IEEE 30-bus test system and results are promising and produce high-quality close-to-optimal solutions. The problem formulation and results are discussed in the following sections.

2. Problem Formulation

Taguchi method is used to find the optimal setting of OLTCs to improve voltage stability margin and to decrease the real power loss. Voltage stability of the system is measured in terms of L-index [12]. L-index varies between 0 and 1 from no load to voltage collapse condition. Lower value of L-index shows improved voltage stability margin. The objective of the proposed work is to find optimal tap settings of different OLTCs so as to minimize the active power loss and L-index of the system while considering different operating constraints [13]. The problem of finding optimal tap settings of OLTCs can be formulated as multi objective problem with the following objectives and constraints:

2.1. Minimum real power loss

Real power loss P_L of the system is function of bus voltages, phase angles, and conductance of line. Thus, first objective of real loss minimization can be expressed as:

$$min\ (P_L) = \sum_{x=1}^{n} G_x (V_i^2 + V_j^2 - 2V_iV_j cos\theta_{ij}) \qquad k = i, j \tag{1}$$

2.2. Minimum L-index

L_j -index of a bus - j shows the voltage stability of the j^th bus. L-index of a system is defined in following way:

$$L = \max (L_j)\ \forall\ j \in 1, 2, ---, n_l \tag{2}$$

Where, n_l indicates the number of a load bus.

Lower value of L-index shows the improved voltage stability margin. Therefore, second objective of enhancement of voltage stability margin (VSM) can be expressed as:

$$\text{Max (VSM)} = \min (L) = \min \{\max (L_j)\} \tag{3}$$

The multi-objective problem can be converted into single objective problem by combining Eq2 and Eq 3 in following way:

$$\text{Min (F)} = \lambda_1 * \min (L) + \lambda_2 * \min (P_L) \tag{4}$$

where, $\lambda_1$and λ_2 are weighing factors. The objective function is minimized using Taguchi method subject to equality and inequality constraints:

3. Taguchi Method

Taguchi Method (TM) is a process optimization method with minimum engineering resources. Taguchi Method is used in the proposed research to find optimal settings of tap positions of OLTCs to minimize the real power loss and L-index. Taguchi Method offers a small set of combinations of tap settings for optimal solution. One of these combinations is optimal solution. TM is briefly discussed below to appreciate its application potential.

The general steps engaged in TM are as follows:

1. Define the objective, or more specifically an optimal value to measure the performance of the process.
2. Identify the factors, which affect the operational process. The factors are variables, which affect the

performance of output. The number of levels for factor variation must be specified.

3. Orthogonal Array (OA) for factorial design is created, which indicates the conditions of each experiment. The OA selection is based upon number of factors and the variation in levels.
4. Conduct the experimental trials for given OA to collect data for analysing the effect of output value.
5. Complete the analysis to identify the optimal objective.

The flowchart of TM design of experiment is shown in Fig.1.

4. Results and Discussions

The potential of proposed method is tested on IEEE 30-bus test system. This system comprises of 30 buses, 41 lines, and 4 transformers with OLTC arrangements [14]. OLTCs $T_1 - T_4$ are connected in the lines 6-9, 6-10, 4-12, 27-28 respectively. The effect of tap changing operation of different OLTCs on parameters of power systems is investigated. On the basis of the study, critical transformer is identified. Thereafter, Taguchi method is employed to find the optimal tap-settings of OLTCs to minimize the real power loss and L-index. The effect of optimal tap-settings on congestion of lines is also investigated. The results of simulations are presented below.

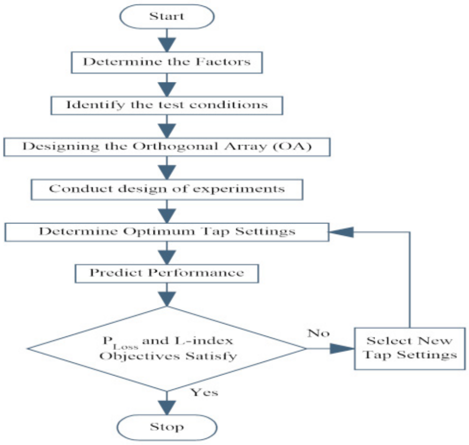

Fig. 1 Flowchart representing Taguchi method

4.1. Effect of tappings on nodal voltage

It is well known that the OLTC's operation has a substantial impact on nodal voltages. In order to examine the effect of tappings on the nodal voltage, tappings are varied under heavy reactive loading conditions. The tap ratio is varied in the steps of 0.0125.The effect of variation in tapping of T_1 on voltage of bus 29 is shown in Fig 2(a). The figure shows that as tap ratio is increased from 0.9-0.9625, the voltage of bus 29 increases from 0.958 p.u. to 0.967 p.u. The variation of voltage of bus 29 for other OLTCs ($T_2 - T_4$) is also shown in Fig. 2 (b) -(c). It is observed from Fig. 2(d), that voltage of bus 29 is improved in the tap range of (0.9-0.9625). However, if tap ratio is above 0.9625, the voltage suddenly dips and this pattern is continued thereafter. This observation reveals that transformer T_4 loses its effectiveness of voltage regulation above 0.9625 tap ratio.

4.2. Effect of tappings on active power loss

The effect of variation of tappings of different OLTCs on active power loss of the system is also studied. Fig. 3 (a)-(c) shows the variation of tappings of T_1, T_2, T_3 on total active power loss of the system. Power loss is varied in the range of 46.4 MW to 46.8 MW, as tappings T_1- T_3 is varied from 0.900 to 1.100. But OLTC of T_4 shows different the behavior above tap ratio of 0.9625. The power loss increases from 46.2 MW to 47.6 MW when tappings are varied from 0.9625 to 1.100.

4.3. Identification of critical transformer

The simulation results of sub-sections 4.1 and sub-section 4.2 are used to find the critical OLTC of the system. These observations reveal that as tap setting is raised above 0.9625, the transformer T_4 loses its effectiveness. After that, with increase in tappings, the voltage of receiving end decreases, line current, real power loss and L-index increases. It shows that transformer T_4 becomes critical when tappings are above 0.9625.

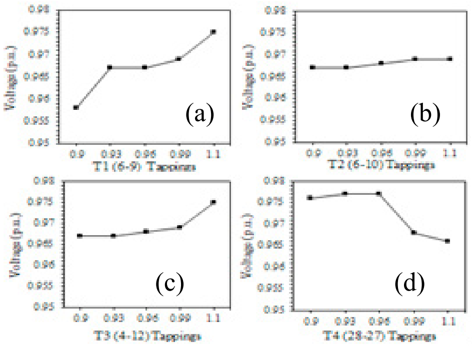

Fig. 2. Voltage profile of bus 29 at different tappings having reactive loading at bus 30

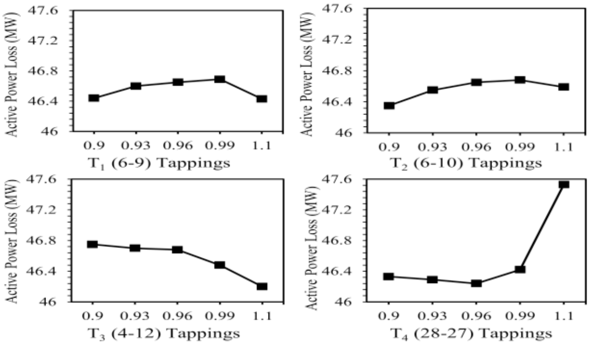

Fig. 3. Active power loss for different tappings

4.4. Optimal coordination of tap settings using TM

Once critical transformer is identified, its tap settings are varied in the range of 0.9000 to 0.9625, since above 0.9625 tap ratio T_4 loses its effectiveness. Now objective is to find the optimal tap settings of T_1¬T_4, so that system loses can be minimized and L-index can be improved. For this purpose, Taguchi smaller the better method is employed. The tap settings of T_1 to T_3 is varied in the steps of 0.0125. In the range of 0.9-1.1, while for T_4, range 0.9 to 0.9625 is selected. Tables I and II depicts the possible tap settings and their levels. Taguchi method optimally picks up only 102 combination to be tried. It saves the time and effort significantly. The design of L_{102} OA is shown in Table III. Out of these combinations, TM optimally selects the best coordinated combination, thus reducing the time and efforts significantly. Optimal tap setting of T_1 to T_4 are found to be 1.100, 0.9875, 1.025, 0.9125 respectively. These results are also compared with hybrid differential approach [9] as shown in Table IV. Total active power loss of 45.561 MW is obtained, when tap settings is chosen according to proposed method whereas line losses are 46.121 MW when tappings are based upon HDE [9]. L-index of different buses are also compared and shown in Fig. 4. There is remarkable improvement in voltage stability margin as L-index of most of the buses is found to be lower than HDE technique [9].

TABLE I Transformer with control factors and levels.

Factors	Tap Levels of OLTCs				
	T_1	T_2	T_3	--	T_{17}
Transformer T_1	0.9000	0.9125	0.925	--	1.100
Transformer T_2	0.9000	0.9125	0.925	--	1.100
Transformer T_3	0.9000	0.9125	0.925	--	1.100

TABLE II Critical transformer with controlled levels.

Factor	Levels of OLTC				
	T_1	T_2	T_3	--	T_6
Transformer T_4	0.9000	0.9125	0.9250	-	0.9625

TABLE III L_{102} (17^3 x 6^1) orthogonal array factors and levels.

Trial No.	Tap Levels of OLTC			
	T_1	T_2	T_3	T_4
1	1	1	1	6
2	1	4	10	4
-	-	-	-	-
-	-	-	-	-
100	17	6	7	4
101	17	8	11	2
102	17	9	13	1

TABLE IV Comparative analysis of PLoss between HDE and proposed TM.

Parameters	HDE [9]	Proposed TM
P_{Loss}	46.121 MW	45.561 MW
T_1(T6-9)	0.9875	1.1000
T_2(T6-10)	0.9125	0.9875
T_3(T4-12)	0.9125	1.025
T_4(T28-27)	0.9000	0.9625

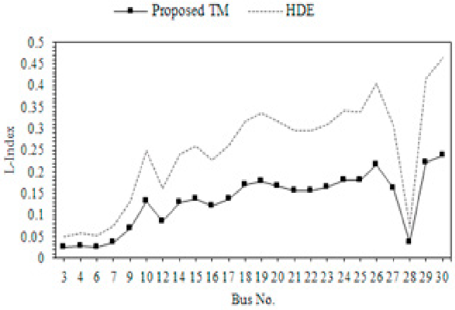

Fig 4. L-index comparison between proposed method and HDE.

5. Conclusions

This paper has proposed Taguchi based method to identify the optimal tap settings of different OLTCs of the system. Critical transformer and its critical value of tap ratio is also identified. Above critical tap ratio, the critical transformer loses its effectiveness. If tappings are raised above critical value, the voltage is pulled down, voltage stability margin decreases, line current and real power loss of the system increases. Optimal tap settings based upon proposed method for a given load optimizes the overall performance of the system.

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Biography

Prof. Ramesh Bansal has over 25 years of experience and currently he is Professor and group head (Power) in the Department of ECC Engineering at the University of Pretoria. He has published over 250 papers. Prof. Bansal is an Editor of IET-RPG & Electric Components and Systems. He is a Fellow, and CEngg IET-UK, Fellow Engineers Australia and Institution of Engineers (India) and Senior Member-IEEE.