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ARTICLE

Optimal PV Allocation & Minimal tap-Changing Transformers Achieving Best Distribution Voltage Profile & Minimum Losses in active distribution networks

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ABSTRACT

In distribution systems, voltage levels of the various buses should be maintained within the permissible limits for satisfactory operation of all electrical installations and equipment. The task of voltage control is closely associated with fluctuating load conditions and corresponding requirements of reactive power compensation. The problem of load bus voltage optimization in distribution systems that have distributed generation (DG) has recently become an issue. In Oman, the distribution code limits the load bus voltage variations within ±6% of the nominal value. Several voltage control methods are employed in active distribution systems with a high share of photovoltaic systems (PV) to keep the voltage levels within the desirable limits. In addition to the constraint of targeting the best voltage profile, another constraint has to be achieved which is the minimum loss in the distribution network. An optimised solution for voltage of load busses with on-load tap-changing (OLTC) tarnsformers and PV sources is presented in this paper. This study addresses the problem of optimizing the injected power from PV systems associated with the facilities of tap-changing transformers, as it is an important means of controlling voltage throughout the system. To avoid violating tap-changing constraints, a method is depicted for determining the minimal changes in transformer taps to control voltage levels with distributed PV sources. The taps of a range + 5 to -15 %, can be achieved by tap-changing transformers. The OLTC operation was designed to keep the secondary bus within the voltage standard for MV networks.

1. Introduction

Recently, the integration of distributed generation gives rise to many challenges to distribution operators. A distribution network integrated with PV is termed active distribution network. The problem of voltage control in radial networks has been studied in several literatures [1]. Different methods for allocating PV sources in distribution systems including transformers with tap-changing facilities [2-6]. Althougth these methods are efficient, it needs more steps and computational time than the presented method. Most of transformers have a motorized on-load tap-changers (OLTC) that adjusts the transformer turns ratio, typically in steps of 1.25% and are utilized to improve the voltage profile of high and medium voltage (HV&MV) grids [7]. Some transformers have no-load tap

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changers (NLTC). These transformers need to be taken out of service to change the tap, which is not advisable in modern smart grid operations. The OLTC is normally controlled by an automatic voltage regulator AVR relay that increases or decreases the tap positions of the transformer. The transformer OLTC are usually at its HV side as the current of this side is lower and there are more turns are available. This makes the voltage regulation more precise. The switching signals to the OLTC transformers can be automated using an automatic voltage controller either local or at a control centre.

The increased constraints, number of dicision variable, and nonlinearity of the DG optimization problems, especially in the case of distribution networks with DGs, made the exact methods incapable of solving such problems without a number of simplifying assumptions that significantly reduce the solution accuracy [9].

This paper investigates the optimum voltage control strategy in busses equipped with load tap-changing transformers and PV sources in radial networks. Several voltage control methods are employed in power systems to keep the voltage levels within the desirable limits. Some of these methods of voltage control in power systems are summarized. The excitation control and voltage regulators at the generating stations provide the basic means of voltage control to maintain the voltage at its scheduled level. There are other additional techniques to control the voltage using reactive power injection or absorption by reactors, synchronous condensers, shunt capacitors, static var compensators SVCs, Flexible AC transmission (FACT) devices and tap changing transformers. These techniques can be applied at sending or receiving end of transmission and distribution lines in industries, substations, and distribution substations to maintain the voltage levels within the standard limits. The users' load connected to the distribution network are devices, which operate at a voltage of a nominal value. If that value drops or increases it will affect the operation of that device and it may damage it, therefore it was needed to have a voltage control method to keep the voltage at its normal nominal value [5].

The voltage control of distribution systems is obtained basically by changing tap position of on-load or off-load tap changers. Off-load tap changing adjustments are usually for seasonal load variations of the special operational requirement of local substations and adjusting the voltage in distribution transformer at the consumer end. On the other hand, on-load tap changing is employed for changing the turn-ratio of the transformer to regulate the system voltage while the transformer is delivering the load. By changing the turns ratio of the transformer both the voltage ratio and the secondary voltage are changed. Tap changing is widely used voltage control method employed at every voltage level. The disadvantage of using OLTC is the voltage collapse due to discrete OLTC switching at intervals of tens of seconds because of the interaction of OLTC dynamics, system loading, and generator reactive power limits. In this case, OLTC blocking can forestall voltage collapse.

This paper investigates the optimum PV allocation strategy in active distribution systems in conjunction with minimal taps of OLTC transformers compared with the case if no tap changing transformers are available. The adopted range for the OLTC has been decided based on datasheets of manufacturers of distribution transformers with tap-changing capabilities.

2. Problem Formulation

Most types of optimization functions in the Engineering applications are as constrained optimization problem. The voltage control by minimum tap changes with PV connected to transformer buses can be cast into a nonlinear constrained optimization. The constrained multivariable optimization problem with an objective function that needs to be maximized or minimized, is followed with constrains functions. The objective function to be minimized is to: (1) minimize the bus voltage deviations from 1 p.u. to achieve the best voltage profile, (2) minimize the transformers tap deviation from 1 p.u so as not to violate the taps limits, and (3) minimize system losses. The function minimization is subject to the constraints of load flows in the active distribution network.

The problem is stated mathematically as finding the tap settings T and PV active power injections so that the 'objective function' for the n-bus radial system is minimized for the radial system shown in figure 1.

$$\min J=(V-1)^t A(V-1)+(T-1)^t B(T-1)+\sum P_{Loss} \tag{1}$$

Subject to the load flow constraints.

$$T_n V_n - T_{n-1} V_{n-1} = \frac{R_{n-1}(P_1 + \Sigma P_{Loss(n-1)} + P_{n-1}) + X_{n-1}(Q_1 + \Sigma Q_{Loss(n-1)} + Q_{n-1})}{T_{n-1} V_{n-1}} \tag{2}$$

Where:

A and B are positive definite diagonal element matrices will determine the relative importance of bus voltage deviation and changes in taps to be as close as possible to one p.u. Matrix A is a diagonal unity matrix multiplied by an accelerating α factor.

$V=[V_1 \angle 0, V_2 \angle \delta_1, \ldots, V_n \angle \delta_{n-1}]^T$, The vector $1 =[1, 1,\ldots,1]^T$, $T=[T_1, T_2, \ldots, T_n]^T$

For any section in distribution networks, the phase

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angle between voltages at that section can be neglected. Hence, we get

$$\sum \mathbf{P}_{\text{Loss}} = \frac{(T_2\, V_2)^2 - (T_1\, V_1)^2}{|Z_1|^2} R_1 + \frac{(T_3\, V_3)^2 - (T_2\, V_2)^2}{|Z_2|^2} R_2 + \ldots$$

$$\sum \mathbf{Q}_{\text{Loss}} = \frac{(T_2\, V_2)^2 - (T_1\, V_1)^2}{|Z_1|^2} X_1 + \frac{(T_3\, V_3)^2 - (T_2\, V_2)^2}{|Z_2|^2} X_2 + \ldots$$

The resulting equations can be put in a compact form as follows:

$$\begin{aligned} \boldsymbol{g} &= [g_1, g_2 \ldots\ldots\ldots\ldots\ldots g_{n-1}]^T \\ &= [0\,, 0 \ldots\ldots\ldots\ldots\ldots 0]^T \end{aligned} \tag{3}$$

where

$$g_{n-1} = T_n V_n - T_{n-1} V_{n-1} - \frac{R_{n-1}(P_1 + \ldots + P_{n-1}) + X_{n-1}(Q_1 + \ldots + Q_{n-1})}{T_{n-1} V_{n-1}} = 0 \tag{4}$$

In this paper, a method is introduced to solve a constrained optimization problem of allocating PV sources in electrical networks with bus voltage constrains. The method of minimal taps of OLTC transformer is used taking into account the line losses and percentage of PV penetration.

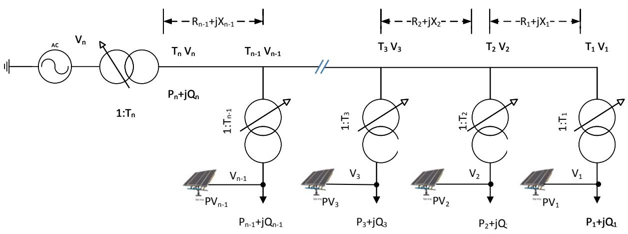

Figure 1. Radial System under study with PV penetration

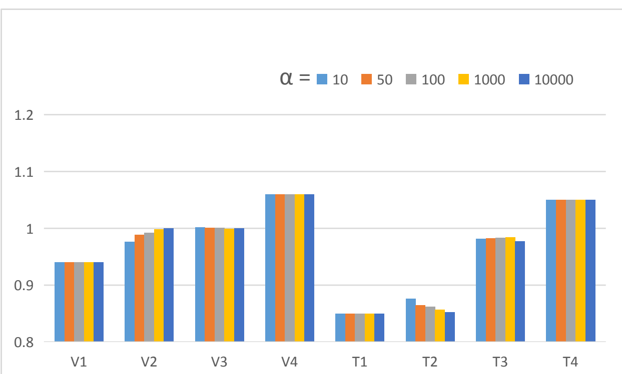

Figure 2. Optimized Values of PV penetration Transformer taps in per unit at variable α factor

Under normal loading conditions, voltage control requirements will be maintained within transformer tap limits. Hence, the weighting matrices A and B could be chosen with equal weight. On the other hand, under extreme heavy loading conditions adjusting the voltage levels to their desired levels could call up taps outside their physical limits. To avoid tap violation outside their physical limits, the control algorithm is penalized by choosing the elements of the matrix B much larger than those of matrix A. The PV penetration will improve the voltage level as well with a constrained level of maximum 20 % of the load level at that paricular bus. This will result in relaxed voltage profile. If the losses are only minimized, the volatge provile may be violated during the optimization of the PV system allocation [9]. This is why both voltage and transformer tap constraints should be taken into account.

3. Problem Solution

There are two approaches to solve the above constrained nonlinear optimization problem: (1) to transform it to unconstrained one using the Lagrangian multiplier method, or (2) to solve it directly as a nonlinear optimization problem.

The voltage control problem is cast into minimizing the objective function J subject to the load flow equality constraints. The problem is that we wish to minimize J subject to the constraint g=0.

A solution can be found using the method of Lagrangian multipliers. There will be a penalty vector λ for too big constraints called Lagrange multiplier vector. Therefore, the Lagrangian of the problem is

$$L = J + \lambda^t \cdot g \tag{5}$$

L is the Lagrangian which will be the unconstrained function, J is the objective function in the constrained optimization problem, λ is the Lagrange multiplier vector, g are the constrain functions of constrained optimization problem.

The constrained nonlinear optimization problem will be solved by the direct method approach. Therefore, it is required to minimize J (1), subject to the power flow constraints g =0 in (4). The above method is applied to a typical radial networks similar to those in Oman's power system as shown in Figure 1.

4. Improved Optimization Technique

In this section, the simulation results relevant to part of a distribution network in Oman are presented. Minimizing the objective function J (1) subject to the constraints g (3) can be solved directly as a constrained nonlinear optimization problem using the function "fmincon" in MATLAB©

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for different values of α coefficient (α =10, 10^2, 10^3, 10^4, . . .).

Applying an increasingly active and reactive load by 7% each year for four years for system of figure 1, there was no voltage violation and the results are within the acceptable limits (±6%). The results can be summarized by the following table 1A for different values of the accelerating factor and an increasing load up to year 2022.

Therefore, this method can be used to produce a good voltage profile by just optimizing the tap-changer of transformers in the presence of PV distributed generation. Results recorded in table A1 and figure 2 show a tight control grip will be carried out over the bus voltage profile for higher α values. However, PV supports the voltage within standard range.

The methods of this paper could be applied successfully in a real network. To make the operation in the network more smarter, sensors and mearing IED devices send the required signals to a central computer [10]. The optimized values of transformers taps and PV output power are then sent back to each bus to control the bus voltages hense the line losses. During partial or no solar insolation, a trade-off has to be done between energy storage or other renewable energy sources.

5. Conclusions

The results here presented show interesting applications of an innovative methodology for voltage control analysis using tap-changing transformers and PV sources, which can become a viable way to achieve consistent and robust voltage control in distribution networks with PV sources. Results show the superiority of the proposed algorithm to the existing ones. This can improve considerably the performance of electrical transmission and distribution systems. The algorithm can be further improved by using online data measurements at each bus with adaptive PV-level penentration.

Appendixes

Table A1. Optimised results for 7% load growth at α=100

$P_{1,2,3}$	2018	2019	2020	2021	2022
V_1	0.9456	0.9400	0.9400	0.9400	0.9400
V_2	0.9988	0.9922	0.9922	0.9925	0.9875
V_3	0.9998	1.0004	1.0004	1.0006	0.9915
V_4	1.0600	1.0600	1.0600	1.0600	1.0600
T_1	0.8500	0.8500	0.8500	0.8500	0.8500
T_2	0.8580	0.8614	0.8617	0.8621	0.8668
T_3	0.9810	0.9820	0.9831	0.9843	0.9942
T_4	1.0500	1.0500	1.0500	1.0500	1.0500
PV_1	0.0250	0.0350	0.0380	0.0410	0.0437
PV_2	0.0300	0.0400	0.0430	0.0460	0.0493
PV_3	0.0270	0.0370	0.0400	0.0424	0.0454
V_{Norm}	0.0810	0.0852	0.0852	0.0852	0.0862
T_{Norm}	0.2134	0.2111	0.2108	0.2104	0.2068
P_{loss1}	0.0404	0.0442	0.0448	0.0459	0.0463
P_{loss2}	0.1705	0.1814	0.1836	0.1856	0.1872
P_{loss3}	0.2681	0.2641	0.2595	0.2548	0.2172

Table A2. Line data

From Bus	To Bus	R [pu]	X [pu]
1	2	0.07	0.19
2	3	0.09	0.195
3	4	0.067	0.184

Table A3. Load data

Bus No.	P [pu]	Q [pu]
1	0.35	0.16
2	0.04	0.19
3	0.37	0.15

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