Var Control Capability Analysis for a Hybrid Voltage Regulation Transformer

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***Abstract*— In modern power distribution systems, power electronics-based devices are designed to provide advanced functions, such as fast voltage regulation, flicker compensation, and var control, which cannot be achieved from the conventional step voltage regulators (SVR). This paper proposed a new topology of the hybrid voltage regulation transformer (VRT), combining voltage regulation and var control into one device. The feasibility and capability of var control are investigated for different load power factors and input voltage range considering the power converter capacity. The simulation results illustrate the feasibility of implementing var control while the load voltage is being regulated. The proposed VRT can regulate the reactive power for each feeder in the distribution system in addition to the voltage regulation function.**

Keywords*— *Hybrid transformer, inverter, var control, voltage regulation

I. INTRODUCTION

Voltage regulation is necessary from portable electronic devices to the power distribution systems to maintain the voltage magnitude. In recent years, voltage variation can be observed more frequently due to renewable energy penetration and the power generation variation from distributed energy resources (DERs). The problem causes today's distribution voltage regulators to operate more frequently due to changing distributed generations, which results in more maintenance and a shorter lifetime of voltage regulators. Fig. 1 shows the conventional SVR configuration which can only regulate the voltage step by step with the speed limit from the tap changer mechanism.

Different power electronics based solutions have been proposed to provide fast voltage regulation and meet the increasing challenge in the grid integration of renewables. Dynamic voltage restorer (DVR) at medium voltage level is discussed in [1] to compensate voltage sags as a cost-friendly solution. And studies in [2]-[5] proposed other DVR functions, such as selective harmonic compensation and fault current limiting. The configuration of DVR is shown in Fig. 2. The DC side of the inverter usually consists of batteries, super-capacitors, or other types of energy storage systems. Therefore, the DVRs are typically utilized to compensate voltage deviation for a short time. In [6], DVR is integrated with a distribution

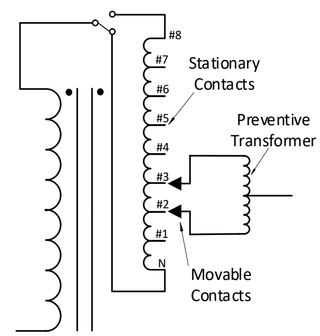

Fig. 1. Conventional voltage regulator

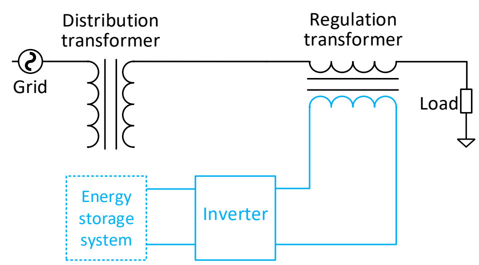

Fig. 2. Dynamic voltage restorer

transformer to achieve step-less voltage regulation, but the regulation speed is still limited by the tap changer mechanism. The static synchronous compensator (STATCOM) is integrated with the distribution transformer in [7] and [8] for the reactive power compensation with a cost-effective method. The smart transformer with full power electronics solution in [8] is rated at the feeder's full power, which is not cost-friendly compared to the previous hybrid solutions [6]-[8]. The study in [10] discusses the var control considerations for the hybrid distribution transformer. But var control capabilities and limits are not investigated when the voltage magnitude regulation is implemented and takes part of the converter capacity.

This paper proposed a new hybrid transformer topology for the voltage regulation at the medium voltage side of the distribution transformer. Section II describes the proposed topology of the voltage regulation transformer and its operation principles, including the benefits of distributed var control. In

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section III, detailed analysis and equations are provided based on different voltage regulation requirements for fixed load voltage magnitude and load voltage with band limits. Var control capabilities and limitations are also investigated for different voltage deviations and load power factors. Section IV presents the simulation results of the var control capability based on different primary side voltages. Section V provides the conclusion and future work discussion.

II. Proposed Hybrid Voltage Regulation Transformer

A. Hybrid Transformer Topology

The configuration of the proposed VRT is shown in Fig. 3. The inverter injects regulation voltage in series from the primary side of the VRT through the upper and lower series transformers. Due to the special inverter output connection and series transformer polarity as shown in Fig. 3, the source current I_S is divided equally through the upper and lower paths as I_H and I_L, as shown in equation (1). With a shunt winding on the VRT supplying energy to the power converter, the series voltage regulation can be implemented constantly without energy limitation.

B. Operation Principle and Equations

To analyze the voltage relationships, the upper and lower series transformer injected voltages are denoted as V_H and V_L. The series transformer turns ratio is N_t. The source voltage, load voltage, and inverter output voltages are V_S, V_L and V_{inv}, respectively. From the transformer winding flux linkage relationship, equation (2) can be derived and the load and source current relationship can be derived as equation (3). In the series transformer loop, the inverter output voltage multiplied by the series transformer turns ratio is the sum of V_H and V_L, as shown in equation (4). And the turns ratio N_t can be adjusted based on the voltage regulation range requirements of the distribution transformers. In equation (5), the load power is the sum of the source power and the inverter output power. By solving equation (3)-(5), the voltage relationships in the proposed VRT can be derived as equation (6). Both rectifier and inverter can provide var control for the system at the same time.

C. Benefits of Var Control with VRT

As the power converter regulates the voltage, there is also var control capability of the power converter if the converter's active power does not exceed the power capacity of the converter. The power converter capacity and the voltage regulation range are rated at 10%. The var control capabilities and the limits are the focuses of the investigation besides the voltage regulation function. The benefit of var control from the power converter is that the power converter can share and coordinate the var control responsibilities with the conventional var control components in the distribution systems, such as capacitor banks, STATCOM, and other types of synchronous compensators. At the same time, the distributed var control can be implemented for each feeder in the distribution system. The distributed var control capability on each distribution voltage regulation transformer relieves the stress of the dedicated conventional var control devices and makes the distribution systems more resilient to var variation of the power distribution systems.

$$I_H = I_L = 0.5\, I_S \tag{1}$$

$$0.5\, n_1 I_S + n_2 I_S = n_3 I_{load} \tag{2}$$

$$I_{load} = \frac{n_2+0.5n_1}{n_3} I_S \tag{3}$$

$$V_H + V_L = N_t V_{inv} \tag{4}$$

$$V_{load} I_{load} = V_S I_S + 0.5 I_S (V_H + V_L) \tag{5}$$

$$V_{load} = \frac{n_3}{n_2+0.5n_1}(V_s + 0.5 N_t V_{inv}) \tag{6}$$

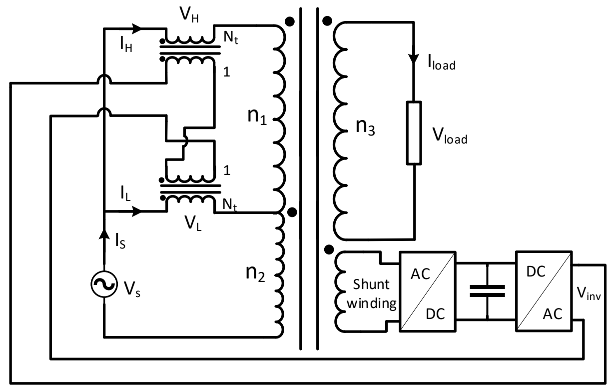


Fig. 3. Proposed voltage regulation transformer

III. Var Control Capability

A. Vector Analysis and Equations

Fig. 4 is the voltage regulation vector analysis for different loading conditions and voltage regulation angle conditions. The blue dashed circle is the target load voltage magnitude, while the brown dashed circle is the injected regulation voltage range. The intersections of the two circles mark the range of the regulated load voltage which can fall on the dashed blue circle between the two intersections. V_{reg} is the injected regulation voltage. V' is the original load voltage at the VRT without voltage regulation. φ_L is the angle between V_{load} and I_{load} which is determined by the load power factor. φ_r is the angle between V_{load} and V' which is determined by the injected regulation voltage. The equations of the two dashed circles can be expressed as equations (7) and (8). By solving (7) and (8), coordinates of two intersections are (9) and (10). The coordinates are the points where the maximum var control is obtained. The load active power and the active power provided by the source can be expressed as equation (11) and (12), respectively. With the exact coordinates of the maximum reactive power points, the angle φ_r can be calculated by equation (13). As the inverter injected active power is the difference of the source and load active power, as equation (14), the maximum reactive power can be expressed as equation (15).

B. Var Control Capability for Fixed Load Voltage Magnitude

It is noted from equation (15) that the var control capability is doubled because the rectifier and inverter can both inject reactive power to the system shown in Fig. 3. The active power

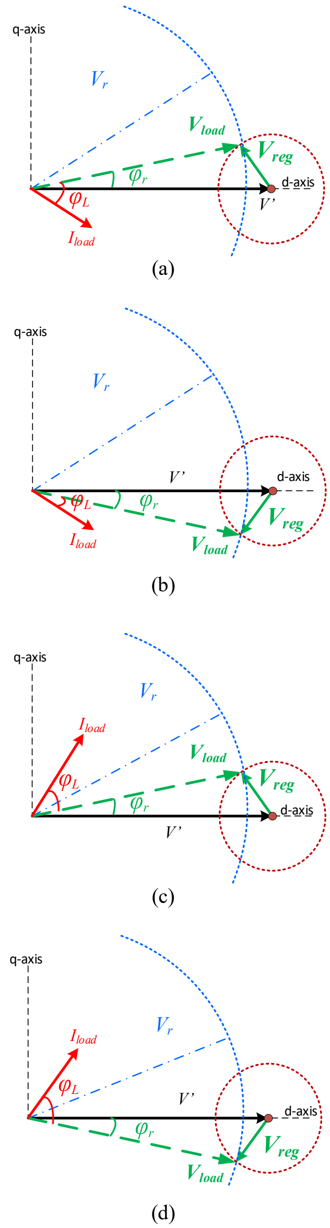


Fig. 4. Voltage regulation vector analysis: (a) inductive load (+φ_L) leading regulation (+φ_r), (b) inductive load (+φ_L) lagging regulation (-φ_r), (c) capacitive load (-φ_L) leading regulation (+φ_r), (d) capacitive load (-φ_L) lagging regulation (-φ_r)

going through the rectifier and inverter is the same, hence the residual reactive power capacity is also the same for two

$$x^2 + y^2 = 120^2 \tag{7}$$

$$(x - V')^2 + y^2 = 12^2 \tag{8}$$

$$x = \frac{7128}{V'} + \frac{V'}{2} \tag{9}$$

$$y = V_q = \pm\sqrt{|120^2 - x^2|} \tag{10}$$

$$P_L = V_{load} I_{load} cos(\varphi_L) \tag{11}$$

$$P_s = V' I_{load} cos\,(\varphi_L - \varphi_r) \tag{12}$$

converters. Based on equation (15), the relationship between the maximum var control capability, load power factor and the input voltage percentage V_{in} can be plotted in MATLAB, as shown in Fig. 5. It can be observed that the var control capability range is the same when the power factor is 1. And the inductive load and capacitive load shows an opposite trend of the maximum var control range when the power factor is not unity. The visualized surrounded area is the var control capability range for inductive and capacitive power load, respectively.

C. Var Control Capability for Load Voltage with Band Limits

For cases where load voltage is only required to be regulated within a band limit, Fig. 6 provides an example of vector analysis when the load voltage is regulated within ±5% band limit. It also applies to more distribution transformer voltage regulation requirements that load voltage is only necessary to be regulated within a certain range, which presents a more flexible var control range for the transformer. The shaded area in Fig. 6 is where the load voltage can be regulated. The maximum var control capabilities are illustrated in Fig. 7. It is indicated in Fig. 7 (c) that the converter can obtain maximum var control when V_{in} is within ±5% range.

IV. Simulation Results

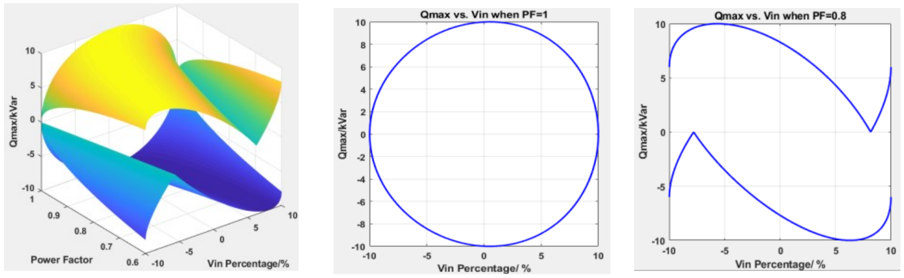
Based on the proposed VRT in Fig. 3, a simulation model is developed to verify the previous analysis on the var control capability. The simulation specifications are listed in Table I. Load in the simulation is modeled as a resistive load and the var control capabilities are investigated for different primary side voltages.

As the source voltage changes, the voltage of the 50kW resistive load is regulated to 120 V and the power converter utilizes the residual capacity to achieve maximum var control points. In Fig. 8, the source voltage is at 7.2 kV rated value. The inverter maximum var control of 5 kVar is achieved from 1 to 1.5 s and the rectifier maximum var control of 5 kVar is achieved from 1.5 to 2 s. As a result, the power converter absorbs the reactive power from the source, which is 10 kVar

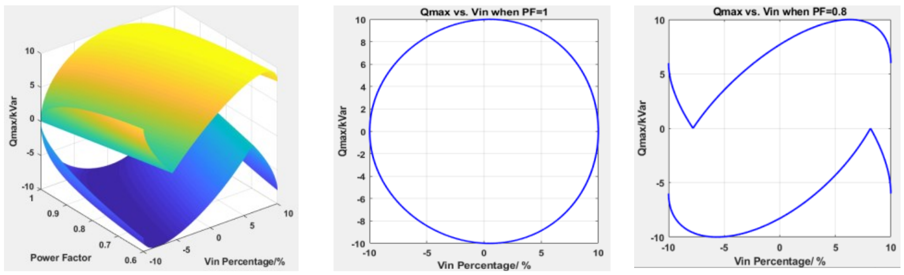
$$\varphi_r = sin^{-1}\left(\frac{y}{V_{load}}\right) = sin^{-1}\left(\frac{\pm\sqrt{\left|120^2 - \left(\frac{7128}{V'} + \frac{V'}{2}\right)^2\right|}}{V'}\right) \tag{13}$$

$$P_{inv} = P_L - P_s = V_{load} I_{load} cos\,(\varphi_L) - V' I_{load} cos\,(\varphi_L - \varphi_r) \tag{14}$$

$$Q_{max} = 2\sqrt{0.1S_{sys}^2 - P_{inv}^2} = 2\sqrt{0.1S_{sys}^2 - [V_{load} I_{load} cos\,(\varphi_L) - V' I_{load} cos\,(\varphi_L - \varphi_r)]^2} \tag{15}$$



(a)



(b)

Fig. 5. Var control capabilities for fixed load voltage magnitude (120V): (a) inductive load ($+\varphi_L$), (b) capacitive load ($-\varphi_L$)

TABLE I. SIMULATION SPECIFICATIONS

Parameter	Value
Power rating	50 kVA
Source voltage	7200 V
Nominal load voltage	120 V
Load current	417 A
Converter capacity	5 kVA
Voltage regulation percentage	10 %
DC bus voltage	400 V
Series transformer turns ratio (N_t)	8:1
Converter switching frequency	10 kHz

in total. In this case, the var control can be obtained in any value within 10 kVar. In Fig. 9, the source voltage is at 7.92 kV which is the maximum rated voltage regulation of +10%. The load power is regulated to 50 kW while the power converter has no residual capacity for the var control. Therefore, the source reactive power is zero during the voltage regulation. The var control capacities when the source voltage is at 0 and +10% regulation correspond to the previous analysis in Fig. 5 when the load power factor is 1.

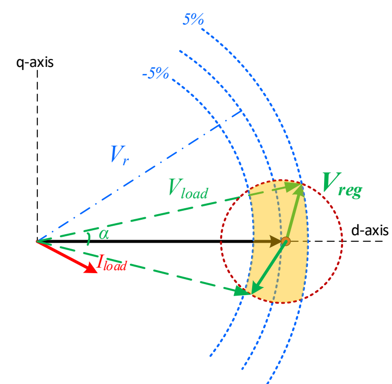
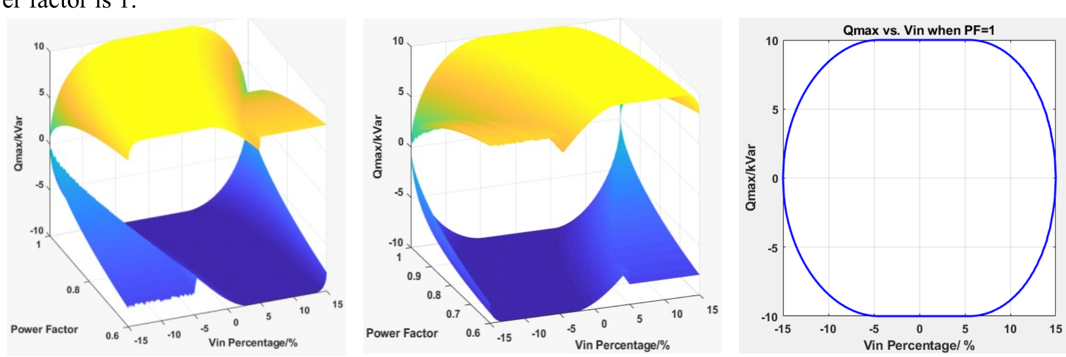


Fig. 6. Voltage regulation with ±5% load voltage band limit

V. CONCLUSION

In this paper, a new voltage regulator topology is proposed for hybrid voltage regulation transformer. The var control capabilities and limits for different input voltage percentages



(a) (b) (c)

Fig. 7. Var control capabilities: (a) inductive load, (b) capacitive load, (c) 2-D plot when power factor is 1

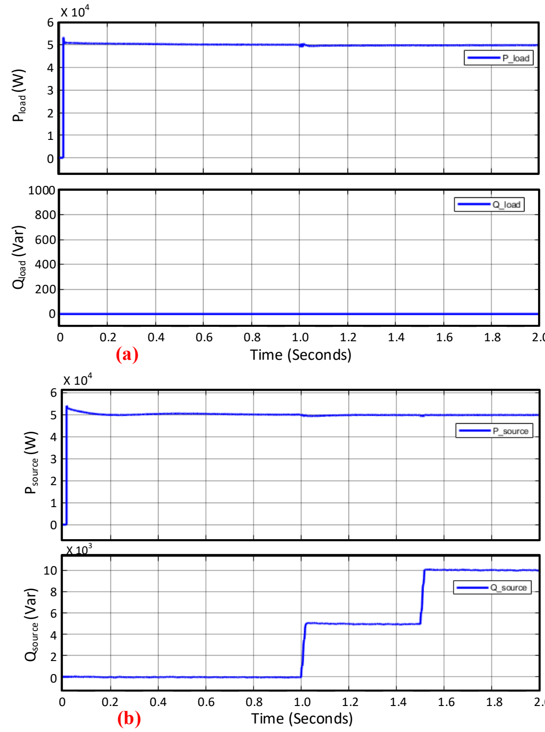


Fig. 8. When V_{source} is at rated 7.2 kV, the active and reactive power of: (a) the load, (b) the source

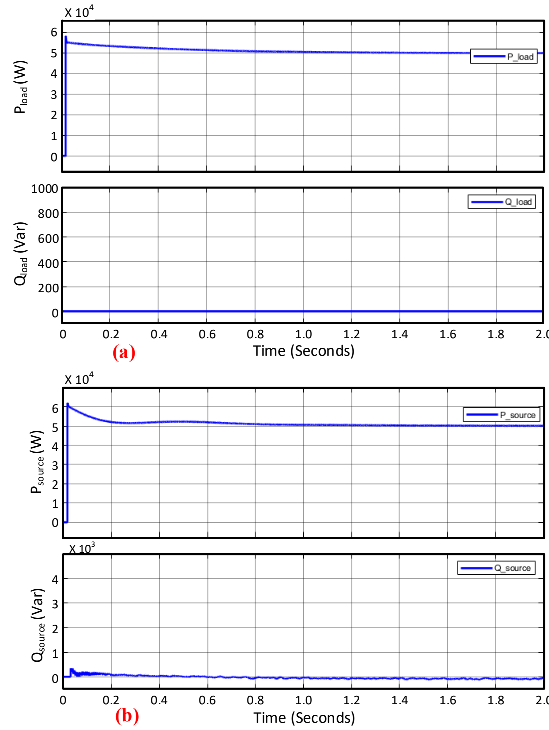


Fig. 9. When V_{source} is at 7.92 kV (+10% variation), the active and reactive power of: (a) the load, (b) the source

and load power factors are analyzed, which helps to fully understand the reactive power compensation capability at different operating conditions. The simulation results validate the feasibility of implementing var control while the load voltage is being regulated. And the var control capability analysis are functionally verified and provide a realistic approach to applying distributed var control in distribution transformers. Var control capability of the VRT can expand the reactive power control capacity of the distribution system and relieve the var control stress on the dedicated conventional var control devices in the distribution system. The advantages and system performance of the distributed var control from the VRT can be further investigated in the future, especially in the medium-voltage large-scale power distribution system with multiple feeders.

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