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Frequency/Voltage Regulation with STATCOM with Battery in High Voltage Transmission System

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Abstract: This paper proposes a method of regulating frequency and bus voltage simultaneously with STATCOM with battery in an high voltage transmission system. Comparative analysis of stand-alone STATCOM and STATCOM with battery is carried out to compare the steady state characteristics of them. Dynamic model and controller are designed to accomplish the two control objectives, frequency and voltage regulation. The results are verified in MATLAB on an modified IEEE 14 bus test system.

Keywords: STATCOM, Battery, Frequency control, Voltage control.

1. INTRODUCTION

Recently, deregulation of power system which requires operation near the maximum efficiency points causes concern for power quality problems such as frequency and voltage deviation. As one of the possible countermeasures to stabilize the power system, flexible AC transmission systems (FACTS) has been getting attention in Ghosh and Ledwich (2012), Satyanarayana et al. (2013) and Khadkikar (2012). Especially, researches on static synchronous compensator (STATCOM) which is a member of FACTS has been mainly conducted over the last two decades. Since it may rapidly inject or absorb reactive power, its application to the voltage regulation has been main research topic in Rao et al. (2000), Norouzi and Sharaf (2005) and Essilfie et al. (2014).

Actually, transmission service providers have been unwilling to install STATCOM mainly due to its low profitability. However, with the recent development of battery technologies, the combination of STATCOM and battery is expected to lead to a more economical choice with improved performance and expanded applicable fields as shown in Yang et al. (2001), Qian and Crow (2002), Singh and Hussain (2010) and Chakraborty et al. (2012). In this combination, STATCOM can not only inject or absorb reactive power but active power with battery as an energy sources. In previous reseaches on this combination, only single function such as voltage regulation in Yang et al. (2001) or damping power oscillation in Singh and Hussain (2010) was dealt with using active and reactive power capability simultaneously. Although those researches are successful in performing single function with better performances than stand-alone STATCOM using two independent control variables (active power and reactive power), it may be more economical to perform two functions simultaneously with two control variables.

In this framework, we consider that the functions which STATCOM with battery performs consist of two parts, active power and reactive power function. As an active power function, frequency regulation has been considered most proper one due to its rapid response in Han et al. (2010) and Lucas and Chondrogiannis (2016). As a reactive power function, voltage regulation can be performed as in stand-alone STATCOM.

In this paper, we analyze the steady state characteristics of STATCOM with battery and derive the dynamic models for it using simplified circuit model. To perform the two functions, frequency and voltage regulation, at the same time, active and reactive power injection are controlled separately by controlling output voltage phase and magnitude respectively through two PI controllers. With this control, frequency and voltage can be regulated at the same time. In conclusion, STATCOM with battery could participate in both services of frequency regulation and voltage regulation. We think that STATCOM with battery could become more economically feasible with this approach.

The rest of this paper is organized as follows. In section 2, comparative analysis of stand-alone STATCOM and STATCOM with battery is presented. In section 3, dynamic model of STATCOM with battery is derived based on equivalent circuit model and controller design of STATCOM with battery are proposed for regulation of both frequency and bus voltage magnitude simultaneously. In section 4, modified IEEE 14 bus test system is introduced for high voltage transmission and simulation is implemented to verify the effectiveness of the proposed approach. Finally, this paper is concluded in section 5.

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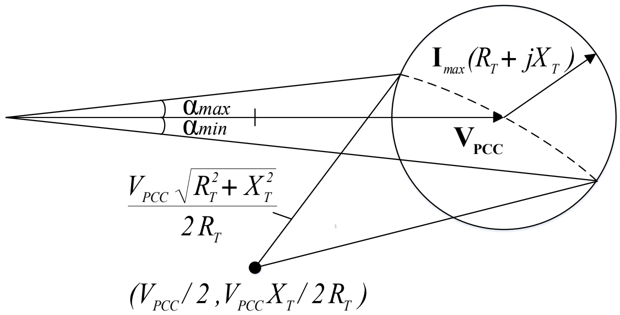

Fig. 1. Phasor diagram of STATCOM output AC voltage.

2. COMPARATIVE ANALYSIS OF STATCOM AND STATCOM WITH BATTERY

STATCOM, one of the shunt type FACTS, is reactive power compensator. STATCOM is particularly good for voltage regulation since it could rapidly inject or absorb reactive power to stabilize voltage deviations. STATCOM is different from other compensators such as static var compensator (SVC) or reactive power banks in that it acts as voltage source through voltage source inverter (VSI) for the power system. The capacitor connected to the DC-link of VSI just maintains DC voltage to make AC voltage at the output side of STATCOM. It means that the compensating performance of STATCOM is not largely influenced by the capacitance of the capacitor which determines the overall compensating performances of SVC and other passive type compensator. The output AC voltage of STATCOM can be expressed as (1),

$$\boldsymbol{E_a} = kV_{DC}\angle\alpha \tag{1}$$

where

- $\mathbf{E_a}$ is a-phase output voltage phasor of STATCOM,
- V_{DC} is the DC link voltage,
- α is the phase of output AC voltage,
- k is a factor that relates the DC link voltage with the magnitude of output AC voltage.

And a-phase current injected at the point of common coupling (PCC) by STATCOM can be represented as (2)

$$\boldsymbol{I_a} = I\angle\phi = \frac{kV_{DC}\angle\alpha - V_{PCC}\angle 0}{R_T + jX_T} \tag{2}$$

where

- $\boldsymbol{I_a}$ is a-phase current phasor injected at PCC,
- I is the magnitude of the injected current,
- ϕ is the phase of the injected current,
- V_{PCC} is magnitude of the PCC voltage,
- $R_T + jX_T$ is the equivalent impedance of transformer between STATCOM and PCC.

Although STATCOM operates as voltage source, it actually cannot supply active power since there is no energy sources for it. It cannot absorb active power as well other than power losses dissipated which arise from switching losses, conduction losses and line resistance to maintain DC-link voltage near constant. This constraint can be expressed as (3)

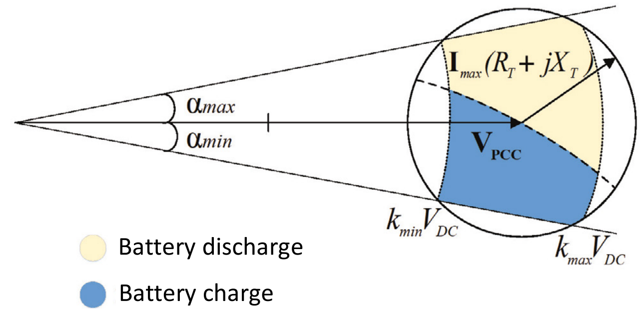

Fig. 2. Phasor diagram of STATCOM with battery output AC voltage.

$$\begin{aligned} P_{STATCOM} &= real(\boldsymbol{E_a I^*}) \\ &= real(kV_{DC}\angle(\alpha)I\angle(-\phi)) = 0 \end{aligned} \tag{3}$$

Substituting (2) into (3) gives

$$E_a = kV_{DC} = \frac{V_{PCC}(R_T cos\alpha - X_T sin\alpha)}{R_T} \tag{4}$$

Equation (4) means that the control variables, α and k, are coupled to each other in steady state and we should control either α or k. Control of α has been preferred to control of k in voltage regulation due to its superior control performance in Yang et al. (2001), Chakraborty et al. (2012) and Singh and Hussain (2010).
By multiplying E_a to both sides of (4), d and q components of $\boldsymbol{E_a}$ in network reference frame must satisfy the equality (5),

$$\begin{aligned} E_d^2 + E_q^2 = E_a^2 &= \frac{V_{PCC}(R_T E_a cos\alpha - X_T E_a sin\alpha)}{R} \\ &= \frac{V_{PCC}(R_T E_d - X_T E_q)}{R} \end{aligned} \tag{5}$$

where $E_d = E_a cos\alpha$ and $E_q = E_a sin\alpha$. Rearranging both sides of (5) gives (6),

$$(E_d - \frac{V_{PCC}}{2})^2 + (E_q - \frac{V_{PCC}X_T}{2R_T})^2 = (\frac{V_{PCC}\sqrt{R_T^2 + X_T^2}}{2R_T})^2 \tag{6}$$

Consequently, $\boldsymbol{E_a}$ must exist on the circle (6) to satisfy zero active power constraint (4) in steady state. Consequent phasor diagram of steady state AC voltage of STATCOM is shown in Fig. 1 where the dashed arc represents (6). I_{max}, α_{min} and α_{max} are determined considering the line impedance, bus voltage and maximum current capacity of STATCOM and transformer. In Fig. 1, α_{min} and α_{max} is somehow large though, they are overstated for illustrative purpose and actually very small due to constraint (4).

STATCOM may interface with battery through its DC link. battery is connected to DC link in parallel with capacitor. In this combination STATCOM with battery may inject or absorb active power, expanding its applicable fields to active power compensating applications such as frequency regulation. The phasor diagram of steady state output AC voltage of BESS/STATCOM is shown in Fig. 2.