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Influence of automatic control of a tap changing step-up transformer on power capability area of generating unit

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ABSTRACT

A synchronous generator is a source of real and reactive power, which can be conveniently regulated over a wide range of values. The real and reactive power of a synchronous generator are limited by the reactive power capability curve, which is determined by the following constraints: stator (armature) current, rotor (field) current, load angle (owing to steady-state stability), the temperature in the end region of the stator magnetic circuit, turbine power, and the terminal voltage of the generator. Large generating units operate on a high-voltage network by using step-up transformers, which can be equipped with on-load tap changers. This article discusses how controlling the transformation ratio of step-up transformers can enlarge the area surrounded by the reactive power capability curve. Equations suitable for such an analysis are derived, and a numerical example is presented. A new control algorithm for tap changing is proposed.

1. Introduction

Reactive power supplied by a generating unit to a transmission network is limited mainly by the rotor current limiter and permissible changes in generator terminal voltage. The influence of these limitations can be decreased by controlling the transformation ratio of the step-up transformer.

Some operators of transmission networks recommend using tap changing transformers as step-up transformers for large generating units. In the grid code [1] a milder requirement is set, that the use of tap changing transformers shall be dependent on the role of generating units in the electric power system and whether an owner of a generating unit wants to offer his regulatory capacity to the operator.

In recent years, the need to enlarge the regulatory capacity of generating units has been increasing. This results from changes in the daily demand curve and from a growing contribution from intermittent sources (e.g. wind farms, solar farms) in total electricity generation. It is expected that large regulatory generating units will be able to work within a broad range of changes with the ability to generate a large reactive power into the system (overexcitation) during the peak demand hours and to absorb a large reactive power from the system (underexcitation) during the off-peak demand hours.

This article discusses the influence of the on-load tap changing control of a step-up transformer on the power capability area of a generating unit.

2. Mathematical model

The power capability curve of synchronous generator is usually specified through a characteristic $P(Q)$ on a plane with coordinates corresponding to the real power and reactive power of a generator, assuming that its terminal voltage is a parameter [2–7]. In this article, a characteristic $P(Q)$ is presented on a plane with coordinates corresponding to the real power and reactive power of the generating unit on the high-voltage side of the step-up transformer (power supplied to a transmission network). The transformation ratio of this transformer is treated as the control variable.

The analysis will be carried out based on an equivalent circuit diagram of a transformer presented in Fig. 1. For high voltage power system elements the resistance is much less than the reactance i.e. $R << X$ and therefore it is very common [2–6] for simplified analyses to omit the resistance and to take into account only the reactance. It is assumed that the synchronous generator is modelled by synchronous electromotive force $\underline{E}_{\mathrm{q}}$ behind a synchronous reactance, i.e. $\underline{Y}_{\mathrm{g}} = 1/\underline{Z}_{\mathrm{g}} \cong 1/\mathrm{j}X_{\mathrm{d}}$. The step-up transformer is modelled by a series branch $\underline{Z}_{\mathrm{T}} \cong \mathrm{j}X_{\mathrm{T}}$ and an ideal transformation ratio ϑ inserted on the secondary side of a transformer model (Fig. 1a).

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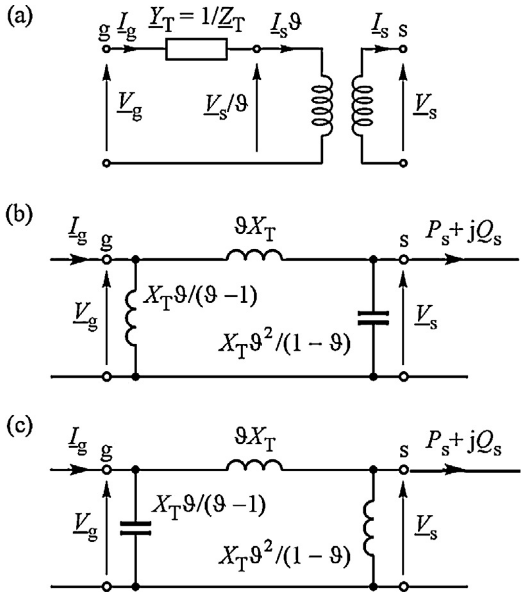

Fig. 1. Equivalent two-port circuits of two-winding transformers: (a) with an ideal transformer, (b) equivalent model for $\vartheta > 1$, and (c) equivalent model for $\vartheta < 1$

It was proven in [2] that a transformer of impedance $\underline{Z}_T$ and ratio ϑ may be replaced with a two-port network of π type, where the admittances of a series branch and shunt branches depend on the transformation ratio (Fig. 1b and Fig. 1c). Such an equivalent model works similarly to a series resonance circuit consisting of inductive and capacitive branches. For $\vartheta > 1$, the shunt equivalent branch at node s is capacitive and inductive at node g (Fig. 1b). Capacitive current flowing from voltage source $\underline{V}_g$ through series reactance ϑX_T to the shunt capacitive branch increases the voltage. For $\vartheta < 1$, the shunt equivalent branch at node s is inductive and capacitive at node g (Fig. 1c). Inductive current flowing from voltage source $\underline{V}_g$ through series reactance ϑX_T to the shunt inductive branch decreases the voltage. It appears from the resonance circuit that the change in the step-up transformer ratio has a significant influence on reactive power.

A generating unit is analysed where the transformer is equipped with an on-load tap changer (Fig. 2a) and the transformation ratio can be controlled. Further analysis is conducted on per-unit values. The voltage on the secondary side of the step-up transformer is divided by the rated voltage of the transmission network. Voltage on the primary side of the step-up transformer is divided by the rated voltage of the generator. An ideal ratio in the transformer model (ϑ) is defined (Fig. 2b) as the ratio of the secondary voltage to the primary voltage. Using the known formulae [2] of the star-delta transformation, the circuit diagram in Fig. 2c may be transformed into the circuit diagram in Fig. 2d. It is noteworthy that in the obtained equivalent two-port network of a generating unit, all of the branches depend on sum $(X_d + X_T)$, which is multiplied by factors that depend on the ratio in the same manner as in the two-port network that replaces a transformer (Fig. 2 and Fig. 2c).

The circuit diagram presented in Fig. 2e is obtained from the initial circuit diagram (Fig. 2b) by bringing the voltage and impedance to the secondary side of the transformer, i.e. the network side.

All of the circuit diagrams presented in Fig. 2 are equivalent and may be used depending on the values that are calculated and the relationships that are searched among them.

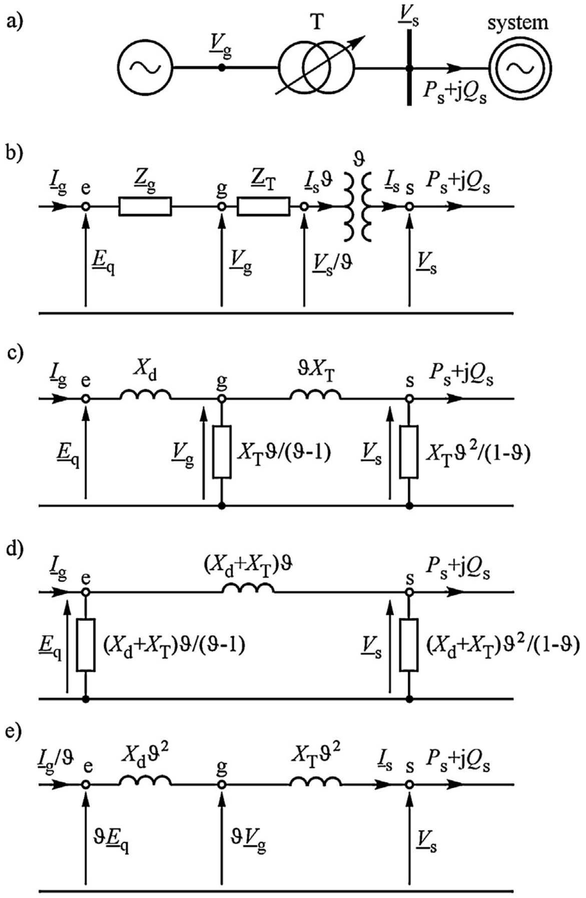

Fig. 2. Equivalent circuit diagrams of generating unit.

For a two-port network consisting of a series reactance X, it can be proven [2] that the output real power and reactive power are given in the following formulae:

$$P = \frac{EV}{X}\sin\theta; \quad Q = \frac{EV}{X}\cos\theta - \frac{V^2}{X} \tag{1}$$

where $\underline{E}$, $\underline{V}$ are voltages across ports, and $\theta = arg(\underline{E}\underline{V})$ is the difference of the arguments of such voltages. It is further assumed that the voltage arguments are calculated with reference to the network voltage: $\underline{V}_s = V_s\angle 0$ and $\underline{E}_q = E_q\angle\delta$, i.e. the difference between arguments of both voltages amounts to δ.

Eq. (1) may be applied in the diagram from Fig. 2e or the circuit diagram from Fig. 2d; however, when calculating reactive power for Fig. 2d, the power of a shunt branch must be taken into account. In both cases, the following is obtained:

$$P_s = \frac{E_q V_s}{\vartheta(X_d + X_T)}\sin\delta \tag{2}$$

$$Q_s = \frac{E_q V_s}{\vartheta(X_d + X_T)}\cos\delta - \frac{V_s^2}{\vartheta^2(X_d + X_T)} \tag{3}$$

Both powers are nonlinear functions of angle δ. This angle is referred to as the load angle.

Real power is inversely proportional to the transformation ratio; and for reactive power, first element is inversely proportional to the transformation ratio and the second element is inversely proportional to the square of the transformation ratio. For given voltages, any change in the transformation ratio results in changes in real and reactive power.

3. Capability area *Q*(*P*)

The capability area of the generating unit, considering control of the transformation ratio, results from the mathematical description of the equivalent circuit diagram in Fig. 2 and the conditions discussed below.

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