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MASTER AND SLAVE CONTROL FOR PARALLEL OPERATION OF EPTS

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ABSTRACT

Parallel operation is a new question caused by EPT being introduced into power system. In this paper, a Master/Slave control strategy for parallel operation of EPTs is proposed. In this control scheme the EPTs are controlled as linear loads for the primary system, but as sources for the secondary system. And one EPT is controlled as a voltage-controlled source and the others are controlled as the current-controlled sources. The voltage-controlled source is developed as a master to establish the voltage of the output common bus and provide CVCF output. The current-controlled sources are operated as slave units to perform current sharing control. Even when the ratings of EPT parallel systems are different, the proposed control strategy can achieve precise current sharing between different rating EPTs. The validity of the proposed control strategy is investigated through simulations with two EPT systems or EPT and conventional transformer hybrid system.

Keywords: *EPT load sharing Master/Slave control parallel operation*

1. INTRODUCTION

Parallel operation of power transformers is usual for increasing reliability and reducing reserve capacity. When conventional power transformers (CPT) operate in parallel, there may be three main problems: (1) circulation current arising from voltage differences, (2) imbalance distribution of loads because of short circuit impedance difference, (3) and complicated grid connected operation. Because CPTs aren't controllable, these problems can't be solved by themselves.

Electronic Power Transformer (EPT) is a novel controllable electric power transmission and transformation device because of power electronic converter and its control technology being applied [1]-[5]. It not only has basic function of power transformer, such as voltage transformation, magnetic isolation and energy transmission, but also implements additional functions: fast voltage regulation, reactive power compensation, and harmonic suppression and so on [5]. Presently, the topologies of EPT have been discussed in many references [1]-[4]. The load characteristics are also discussed in [6]. However, the parallel operation of EPTs has not been mentioned. Although EPT is a controllable transformer, circulation current or imbalance distribution of loads will still exist in parallel EPTs system if there are differences between voltages or line impedances. So, the load sharing

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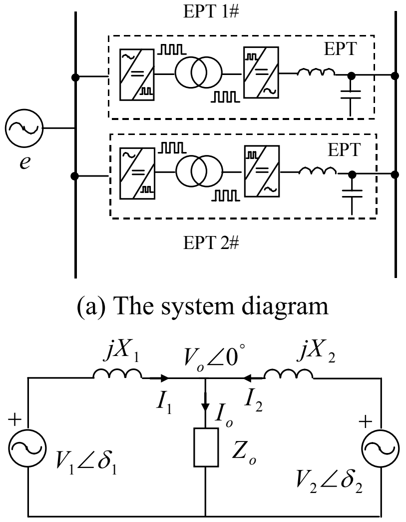
control to maintain the current balance is still critical.

In this paper, the parallel operation of EPTs is investigated in detailed. A current sharing control strategy is introduced. The system consists of a voltage-controlled source and several current-controlled sources.

2. GENERAL PROBLEMS OF PARALLEL OPERATİON OF EPTS

The typical configuration of parallel EPTs is shown in Fig.1 (a).



(a) The system diagram

(b) The equivalent circuit

Fig. 1 *Parallel operation of EPT*

The equivalent circuit of parallel EPTs is shown in Fig. 1(b). V_1, V_2, I_1 and I_2 are the output voltages/currents of EPT1 and EPT2. According to Fig. 1(b), the active and reactive powers can be expressed as

$$P_i = \frac{V_i V_o}{X_i}\sin\delta_i \tag{1}$$

$$Q_i = \frac{V_i V_o \cos\delta_i - V_o^2}{X_i} \tag{2}$$

where, i=1 or 2.

And the currents can be expressed as

$$\dot{I}_1 = \frac{\dot{V}_1 - \dot{V}_o}{jX_1} = \frac{\Delta\dot{V}_1}{jX_1} \text{ and } \dot{I}_2 = \frac{\dot{V}_2 - \dot{V}_o}{jX_2} = \frac{\Delta\dot{V}_2}{jX_2}$$

If $X_1 = X_2 = X$, then

$$\dot{I}_1 - \dot{I}_2 = \frac{\dot{V}_1 - \dot{V}_2}{jX} \tag{3}$$

If $\dot{V}_1 = \dot{V}_2$, then

$$\dot{I}_1 - \dot{I}_2 = \Delta\dot{V}\left(\frac{1}{jX_1} - \frac{1}{jX_2}\right) \tag{4}$$

where, $\Delta\dot{V} = \dot{V}_1 - \dot{V}_o$.

Equation (1) and (2) show the active power (P_i) is predominately dependent on the power angle (δ_i), and reactive power (Q_i) is predominately depend on the voltage amplitude. Equation (3) and (4) indicate that if the voltage amplitude or phase differences occur or the impedance difference exists, the current unbalance will arise. Because the line reactance X is very little, the unbalance is severe. This will decrease the system efficiency, and may cause damage to the power devices in the parallel system [7]. To solve these problems, the special current sharing approach should be introduced to parallel EPT system.

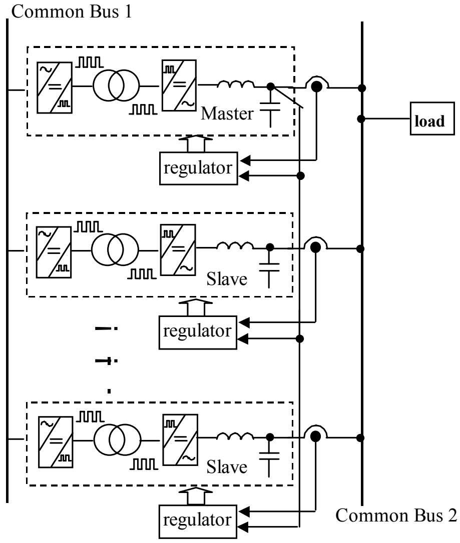
3. THE PROPOSED CONTROL STRATEGY

Master/Slave control technique is applied widely for three-phase parallel inverter and UPS to achieve current sharing [7-8]. It has many advantageous, such as good sharing effect, easily being implemented and not being affected by the line impedance of the interconnecting lines and so on. Unlike current sharing control methods based on power deviation compensation or voltage /frequency droop characteristics, it doesn't need to control the output voltages of all the modules in parallel system synchronous exactly in frequency, amplitude and phase angle. So, we introduce this method into the design of the parallel EPT control system. In order to satisfy the operating requirement of parallel operation of EPTs with different ratings, we control one EPT as a voltage-controlled source and the others as current-controlled sources. The voltage source is the master unit and the current source is the slave unit.

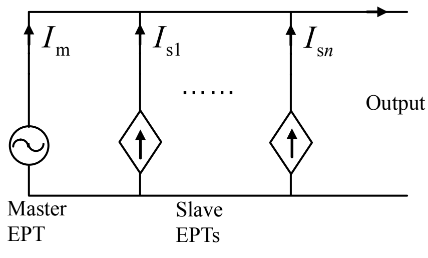
The master EPT provides a constant voltage and constant frequency (CVCF) output to establish and maintain the voltage of Common Bus (CB). The slave EPT provides suitable current output to balance load current. In order to keep EPT stable, the control system should keep power balance between the input and output of EPT.

The typical configuration of the Master/Slave technique for parallel EPTs is depicted in Fig. 2(a) and Fig. 2(b) shows its equivalent circuit.

This configuration has many outstanding characteristics: (1) the system does not need to measure the load current, which makes the system easily expandable; (2) and the line impedance of the interconnecting lines does not affect the load sharing. There are however, a few serious disadvantages. One of the major disadvantages is that the system is not truly redundant. If the master EPT fails, the whole system shuts down.



(a) Configuration



(b) equivalent circuit

Fig. 2 *System diagram of parallel EPTs with Master/Slave control.*

To solve the problem, a signal interconnecting line is set in our control scheme, and the state of the master EPT is "written" on the signal interconnecting line. If the master unit fails, the state will overturn. And one of the slave EPTs will automatically "act as" the master role after detecting the overturn.

A. The Control of Master EPT

There are many configurations of EPT, but we design the control system in detailed for the one of them. A typical EPT topology is shown in Fig. 3. As can be seen, this is a three-part design that includes an input stage, an isolation stage and an output stage. It is suitable to use in distribution system.

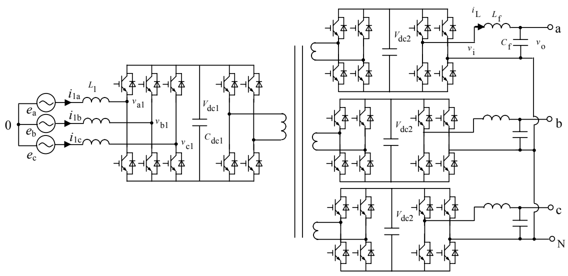


Fig.3 *The typical circuit of EPT*

The control of the master EPT includes the input stage control and the output stage control.

There are two aims for the input stage control of the master EPT: the one is to maintain dc voltage constant, and the other is to make the input current sinusoidal.

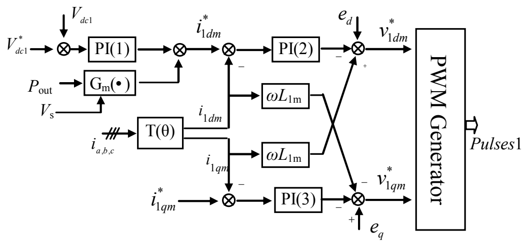
The mathematic model of the input stage of EPT can be presented in synchronous rotating d-q frame reference as (5)

$$\begin{cases} L_{1m}\dfrac{di_{1dm}}{dt} = \omega L_{1m} i_{1qm} - v_{1dm} + e_d \\ L_{1m}\dfrac{di_{1qm}}{dt} = -\omega L_{1m} i_{1dm} - v_{1qm} + e_q \\ C_{dc1}\dfrac{dV_{dc1}}{dt} = i_{c1} \end{cases} \tag{5}$$

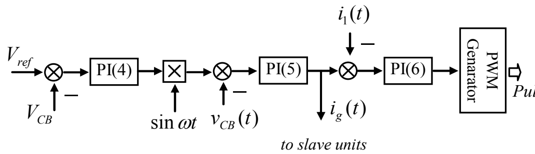
where, ω is the synchronous angle velocity.

Equation (5) indicates that there is a cross coupling between the d axis and q axis, which will influence the system dynamic performance. In order to solve this problem, the current state feed back decoupling and the input source voltage feed forward are applied. The input stage control of the master EPT is shown in Fig. 4(a).

The output stage of the master EPT should provide CVCF output or track and follow the voltage and frequency of the second side system. If considering the second side is a passive system, the constant ac voltage control based on instantaneous value feedback can be adopted. It is shown in Fig.4 (b).



(a) Control of the input stage



(b) Control of the output stage

Fig.4 *Control block diagram of the master EPT*

There are two control loops in the input side control of the master EPT: a dc voltage outer loop and ac current inner loop. The former is to maintain dc voltage constant and the latter is to realize active and reactive power decoupling control. According to Fig. 4(a), the reference for the active current flow i_{1dm}^* is derived from the outer voltage loop. The reference for the reactive current i_{1qm}^* is set independently or derived from the power factor loop. Here, i_{1qm}^* is set to zero to achieve unity power factor. The deviations of current pass through the PI controllers to form the modulation signals. In order to keep EPT stable and improve its dynamic performance, the control system should keep power flow balance between the input and output. So, the output active power is fed back to help generating i_{1dm}^*.

In the Fig.4 (b), V_{ref} is the RMS value of the reference voltage, $i_1(t)$ is the load current and V_{CB} and $v_{CB}(t)$ are RMS value and instantaneous value of CB, respectively. The control of the output stage of the master EPT consists of a voltage controller and current controller. In order to make the voltage of CB constant and sinusoidal, the voltage controller is a double loop: the one is output voltage RMS value loop and the other is the voltage instantaneous value control loop. In order to improve the system performance by eliminating the harmful effects caused by load current disturbances, the load current feedback is introduced.

B. The Control of Slave EPT

The slave EPTs should provide suitable currents to balance load current. They are controlled as current-controlled sources. Each slave EPT control also includes the input and output stage control.

The input stage control of the slave EPT is the same as that of the mater EPT. Here, the output stage control of the slave EPT is only discussed.

In order to eliminate the circulation current caused by amplitude and phase angle differences, the slave EPT performs only current sharing control for its output stage. Fig. 5 shows the current sharing control scheme. In the control scheme, the current reference comes from the master EPT. However, there still is a voltage loop. The functions of the voltage loop are: (1) tracking voltage of CB before connecting parallel, (2) and automatically “acting as” the master EPT when the “real” master EPT is in failure.

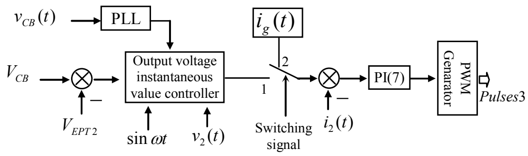


Fig.5 *Control of the output stage for slave EPTs*

4. SELECTION OF COOLING FAN AND FLUE

To verify the proposed strategy, simulations are carried out. The parameters used in the simulation are shown in Table 1. EPT1 is the master and EPT2 is the slave.

Tab.1 *Parameters of the parallel system*

Parameters	Value
Capability of EPT1	1600 kVA
Rated voltage of EPT1	10 kV/400 V
Capability of EPT2	1600 kVA
Rated voltage of EPT2	10 kV/400V
Grid frequency	50 Hz
Load / power factor	1600 kVA / 0.8

Fig. 6-Fig. 8 are simulation results. Fig. 6 shows waveforms of the current when 1600kVA load is put into operation at 0.35 s. It illustrates excellent characteristic for load variation. Fig. 7 shows

waveforms when there are differences of the line reactance between the master and slave EPTs. Fig. 8 shows results when the slave EPT is put into operation at 0.35s while the master EPT is in operation with full load. And then, the master EPT is switched off at 0.4s. It illustrates that the proposed method provides load sharing and fast transient processes. At the same time, the slave can automatically convert to the master.

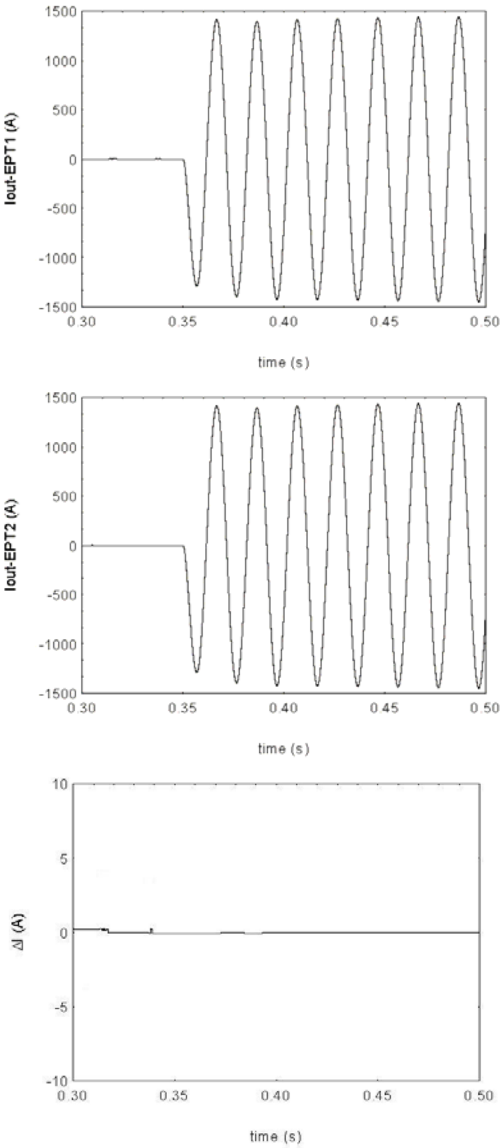


Fig. 6 *simulation results for load variation (waveform of phase A)*

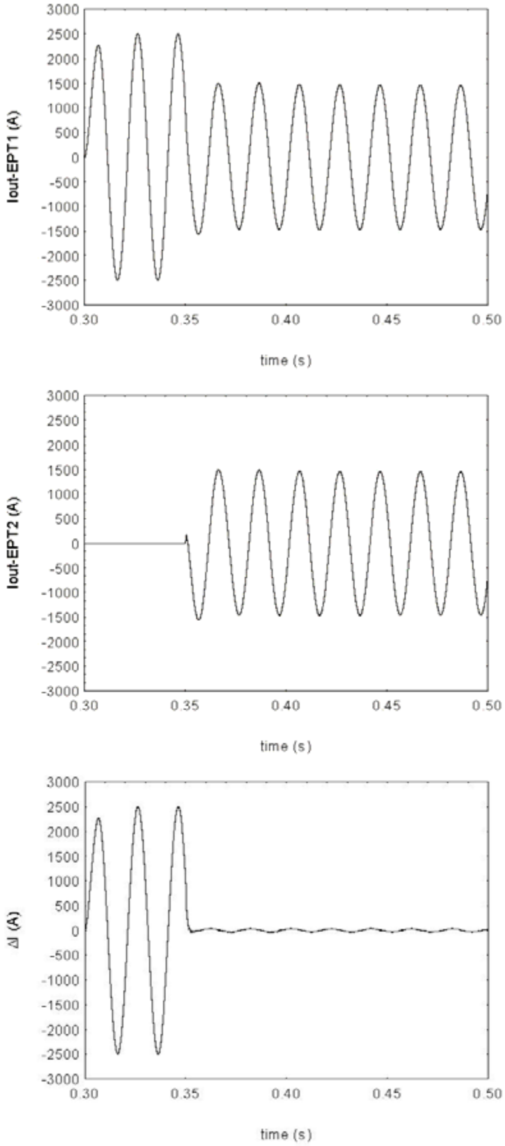


Fig. 7 *simulation results for difference connecting impedance (waveform of phase A)*

The proposed Master/Slave control method can also be applied to parallel EPT system with different ratings. On this operating condition, the reference current of the slave EPT that comes from the master EPT should multiply by the capacity ratio coefficient. For example, if the master EPT's capacity is 1600 kVA and the slave EPT's capacity is 800 kVA, the capacity ratio coefficient is 0.5. Fig. 9 shows the simulation results of parallel system of EPT with different ratings of 1600 kVA and 800 kVA. The load sharing between the master and the slave EPT is divided with the ratio of 2:1.

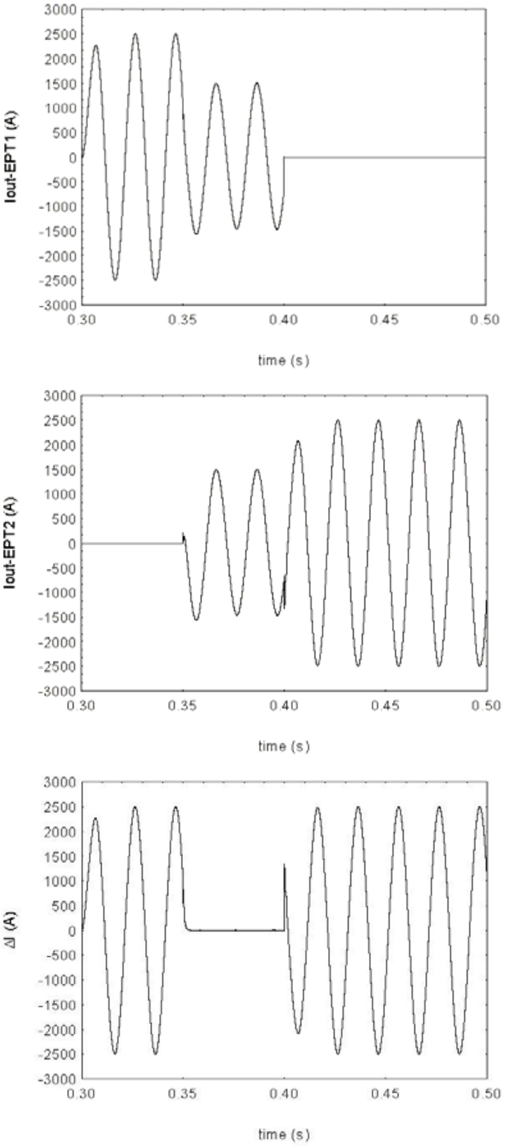


Fig. 8 *simulation results during master EPT failure (waveform of phase A)*

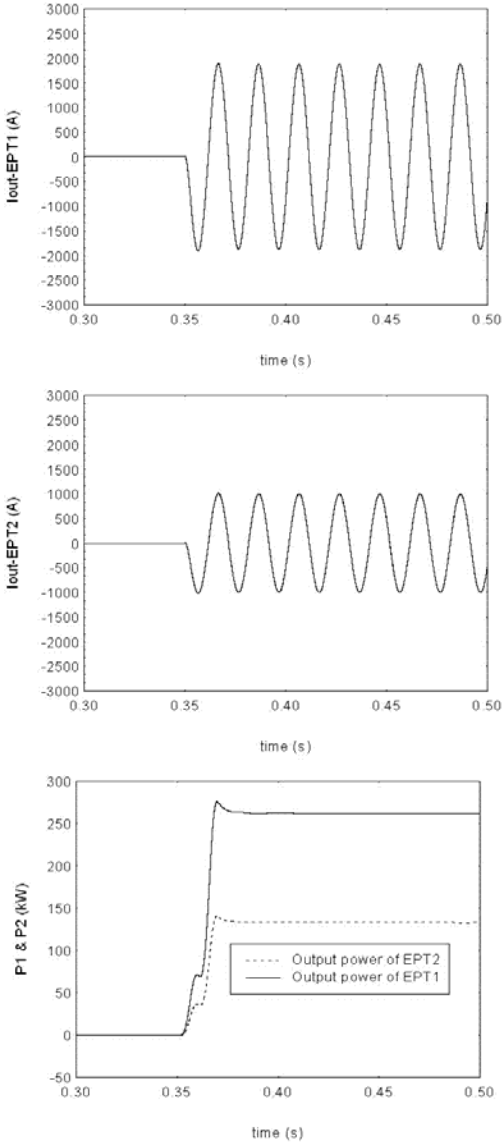


Fig. 9 *simulation results for parallel EPTs with different ratings (waveform of phase A)*

5. CONCLUSION

This paper presents the problems of EPT caused by parallel operation. A Master/Slave control strategy is designed for parallel operation of EPTs. The proposed control strategy can be used for parallel EPTs not only with same ratings but also with different ratings.

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