DC magnetic bias suppression strategy for series transformers in dynamic voltage restorers

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Abstract. In actual engineering, the dynamic voltage restorer is mainly used to protect the load from the voltage drop of the grid, and is inserted between the grid and the load through the series transformer. The dynamic voltage restorer (DVR) can easily cause DC bias and generate magnetizing inrush current at the beginning of compensation voltage drop. This is also a common problem in DVR engineering applications. The usual way to solve this problem is to design the transformer core to twice the rating, but this will greatly increase the size and cost of the transformer. In order to ensure the safe, reliable and stable operation of the DVR and reduce the cost and volume of the transformer, it is necessary to suppress DC bias of the transformer. Based on the principle analysis of the DC bias generation in series transformers, a DC bias suppression strategy was proposed to control the amplitude of the first half of the output voltage of the DVR. The DVR system model was built in Simlpler, Matlab and Maxwell for co-simulation, and the effects before and after the DC bias suppression strategy were compared.

1. Introduction
The Dynamic Voltage Restorer (DVR) is currently an effective approach of solving the instantaneous drop in the grid voltage. It can be equivalent to a controlled voltage source connected in series between the grid and the load. When the grid voltage is normal, the DVR operates in the standby state, monitoring the grid voltage but the inverter does not output voltage. When the grid voltage drops, the DVR immediately switches to the compensation state, and outputs the compensation voltage to the system within a few milliseconds, so that the voltage and phase on the load remain constant, therefore, it can effectively protect the load from normal operation without being affected by the grid voltage drop [1]. Figure 1 is a schematic diagram of the connection and operation of the DVR system.
It can be seen from figure 1 that the DVR system is mainly composed of an energy storage unit, an inverter, a filter and a series coupled transformer. In this topology, due to the high response speed of the DVR, the rapid output of the voltage often causes the DC bias of the transformer [2]-[5], which affects the hysteresis curve of the transformer core. In severe cases, the magnetic saturation of the transformer causes the excitation current to be too large and affects the normal operation of the DVR [6]-[8]. Therefore, how to effectively achieve bias suppression has become a research hotspot of DVR when the grid voltage flickers.

At present, both domestic and foreign are working on the structural design of the transformer, that is, reducing the maximum magnetic flux density of the transformer core and increasing the core cross section, reducing the rated working point of the transformer core and increasing the saturation margin to ensure that there is no oversaturation even if a DC biased magnetic core occurs. [9]-[10]. This method is simple and straightforward and easy to implement, but it will cause the core to be too large. For one thing, the effective material consumption is extremely high. For another thing, when the transformer is running, the iron loss increases and the economy decreases. In addition to a series of problems such as high manufacturing cost, large volume and weight, and inconvenient transportation, it is of great practical significance to start the research on the saturation suppression of the DVR series injection transformer.

2. DC bias magnetic problem generation principle and suppression strategy

2.1. Principle of DC bias problem generation

Figure 2 is a schematic diagram of the basic magnetization curve of a ferromagnetic material. It can be seen from the figure that the magnetic permeability of the ferromagnetic material is nonlinear, and the magnetizing inrush current of the transformer is caused by the DC bias phenomenon of the transformer. When the magnetic flux of the transformer core does not reach the saturation value ($\phi < \phi_s$), the magnetization curve can be approximated as linear, and a small excitation current can generate a large magnetic flux. Therefore, the excitation current required when the transformer operates in the linear section of the magnetization curve is small, and no magnetizing inrush current phenomenon occurs; when the magnetic flux in the transformer core exceeds the saturation point ($\phi > \phi_s$), the magnetization curve becomes non-linear, and the magnetic flux increases when the field current is further increased due to the decrease in magnetic permeability. The amount is gradually reduced, and generating a magnetic flux of the same magnitude requires a large excitation current,
which causes the excitation current of the transformer to be excessive to form a magnetizing inrush current.

\[ u_t = U_m \sin(\omega t + \alpha) \quad (1) \]

Where, \( \alpha \) is the initial phase of the output voltage \( u_t \) at \( t = 0 \).

Then there is the following differential equation at \( t \geq 0 \):

\[ i_t R_1 + \frac{d\phi}{dt} = U_m \sin(\omega t + \alpha) \quad (2) \]

Where, \( \phi \) is the total magnetic flux interlinking with the primary winding, which includes the main magnetic flux and the leakage magnetic flux of the transformer. Since the leakage flux is small, the influence of the leakage flux is ignored in the next analysis. Equal to the main flux. \( R_1 \) is the primary leakage current of the transformer, and \( i_t \) is the primary current of the transformer.

In equation (2), since the transformer leakage resistance is small, the voltage drop \( i_t R_1 \) on the resistor can be neglected in the initial stage of analysing the DVR input compensation voltage, so when the influence of \( R_1 \) is ignored, the equation (2) becomes:

\[ N_1 \frac{d\phi}{dt} = U_m \sin(\omega t + \alpha) \quad (3) \]

The differential equation (3) is solved, and considered that the DVR twice voltage compensation interval is longer. When the transformer flux \( \phi \) initial value is 0 when it is put into operation again, the flux linkage expression can be obtained as follows:

\[ \phi = \frac{1}{N_1} \int_0^t U_m \sin(\omega t + \alpha)\,dt = \phi_m \left[ \cos \alpha - \cos(\omega t + \alpha) \right] \quad (4) \]

Where, \( \phi_m = \frac{U_m}{\omega N_1} \) is the steady state flux maximum.

It can be seen from (4) that the magnetic flux \( \phi \) is composed of a transient component and a steady-state component, wherein the transient component is related to the initial phase angle \( \alpha \) of the input time \( (t = 0) \) voltage, and two extreme cases are considered in Figure 3:
1) When $t = 0$, $\alpha = \frac{\pi}{2}$, at this time, the DVR output compensation voltage $u_l = U_m$ reaches the maximum value, obtained by equation (4):

$$\phi = -\phi_m \cos(\omega t + \frac{\pi}{2}) = \phi_m \sin \omega t$$

(5)

It can be seen that when the input angle $\alpha = \frac{\pi}{2}$, the transient component of the flux $\phi$ is zero, and no DC bias phenomenon occurs. Starting from $t = 0$, the primary current of the transformer establishes a steady state flux $\phi_c \sin \omega t$ in the core without transients. The primary current $i$, of the transformer is also the current during normal operation.

2) When $t = 0$, $\alpha = 0$, then the DVR output compensation voltage $u_l = 0$, obtained by equation (4):

$$\phi = \phi_m \left[1 - \cos \omega t \right] = \phi_m - \phi_m \cos \omega t$$

(6)

It can be known from equation (6) that $\phi_m$ is the transient component of the magnetic flux, and $\phi_m \cos \omega t$ is the steady-state component of the magnetic flux. When a half cycle, $t = \pi / \omega$, elapses from $t = 0$, the magnetic flux $\phi$ reaches a maximum value of $2\phi_m$, and a DC bias phenomenon occurs. Generally, the transformer does not retain twice the margin when designing. At this time, the excessive core flux has exceeded the saturation point of the core material. To generate excessive magnetic flux will inevitably lead to magnetizing inrush current, which will lead to inverter. The output current is distorted, which affects the normal operation of the DVR system. Therefore, it is necessary to take measures to suppress the occurrence of magnetizing inrush current in the actual operation of the transformer.

2.2. DC bias suppression strategy

In order to reduce the voltage loss on the device and the switching loss of the semiconductor device under normal operating conditions of the system, the inverter side of the DVR series transformer is "short-circuited", that is, the upper part (or lower part) of the two bridge arms of the inverter The switching device is turned on at the same time, and a zero voltage vector is injected into the system, as shown in Figure 4 (a). At this time, only the transformer leakage reactance is connected in series in the line. When the voltage on the system side is temporarily suspended, the DVR inverter injects the compensation voltage into the injection operation state from the standby operation state, as shown in Figure 4 (b).
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(a) Standby state                                          (b) Injection state

Figure 4. Operation states of DVR

It can be seen from the foregoing analysis that the core flux $\phi$ of the series transformer is determined only by $U_m$ and $\alpha$, as shown in the following equation:

$$\phi = \phi_m \left[ \cos \alpha - \cos(\omega t + \alpha) \right]$$

(7)

As can be seen from the equation (7), the magnetic flux includes a direct current component $\phi_m \cos \alpha$ and an alternating current component $\phi_m \cos(\omega t + \alpha)$. It can be imagined that if the DVR is injected with a voltage instantaneously, and the DC component of the magnetic flux is 0 by appropriate control, the transformer directly enters the steady state operation state, and there is no transient transition process, that is, the transformer core saturation phenomenon does not occur. The ability to compensate the DC component of the flux to 0 is based on the following two factors: 1) The DC component of the flux is only related to the injected voltage amplitude and the input angle, independent of the voltage frequency; 2) The voltage input angle is the flux DC component is 0.

The idea of the DC bias suppression strategy of the series transformer proposed in this paper is: calculate and control the amplitude of the first half cycle of the DVR output voltage according to the phase angle and the drop depth at the voltage drop, and then realize the control of the core flux of the series transformer. Next, the drop phase angle $\alpha = 0$ and the drop depth 50% are taken as an example for explanation.

In the case where the drop phase angle $\alpha = 0$ and the drop depth is 50%, the series transformer flux expression using the aforementioned suppression strategy is:

$$\phi = \frac{1}{N_1} \left[ \frac{\pi}{2} U_m \sin \omega t dt + \frac{\pi}{\omega} U_m \sin \omega t dt \right]$$

$$= \frac{U_m}{2\omega N_1} \cos \pi + \frac{U_m}{2\omega N_1} \cos 0 - \frac{U_m}{\omega N_1} \cos(\omega t + \alpha)$$

(8)

$$= -\frac{U_m}{\omega N_1} \cos(\omega t + \alpha) = -\phi_m \cos(\omega t + \alpha)$$

It can be seen from the comparison of equations (6) and (8) that after the suppression strategy, the DC flux linkage of the series transformer is effectively suppressed, and the generation of magnetizing inrush current is avoided.

3. Simulation analysis

At present, in most papers, only the single software Matlab is used for the part related to transformer simulation. Although Matlab can realize transformer simulation through the S-Function module, it can not effectively reflect many physical factors such as transformer core material and volume, and can not observe the flux linkage curve and magnetic density of transformer in real time, which has obvious disadvantages and drawbacks.

In order to realize the real-time simulation and observation of the transformer, this paper uses Simploter, Matlab and Maxwell to build a 380V low-voltage DVR system model for joint simulation, and verify the DC bias suppression strategy proposed in this paper. Among them, the main circuit
model of the system is built in Simplorer, DVR voltage compensation and DC bias suppression control module of series transformer are built in Matlab, and a suitable series transformer model is designed in Maxwell. The simulation conditions are as follows: The DVR series transformer is a 1:1 isolation transformer. The voltage of the A-phase grid drops at 0.1s, the drop depth is 0.5 pu, and the 0.2 s voltage returns to normal. Figure 5 shows the voltage waveform of the A-phase grid.

In the case where the series transformer DC bias suppression control module is not added, the A phase load voltage waveform is shown in Figure 6 (a); Figure 6 (b) is the A phase DVR output compensation voltage waveform; Figure 6 (c) is A Phase series transformer flux linkage curve (where, FEA.1.FLUXT1TR is the primary flux linkage curve and FEA.1.FLUXT2TR is the secondary flux linkage curve.). It can be seen that in the uncontrolled state, the DC bias of the series transformer makes the magnitude of the flux linkage reach twice the rated value. If it is operated in this state, the core will be saturated, causing the magnetizing inrush current, which in turn affects the DVR. The system works properly.
Figure 6 (b). Phase A DVR output compensation voltage (No control)

Figure 6 (c). Phase A series transformer flux linkage (No control)

When the control module is added, it can be seen from Figure 7 (c) that the DC bias is effectively suppressed, and the saturation of the series transformer core and the possible magnetizing inrush current are avoided, which ensures the normal operation of the DVR.

Figure 7 (a). Phase A load voltage (Control)
Figure 7 (b). Phase A DVR output compensation voltage (Control)

Figure 7 (c). Phase A series transformer flux linkage (Control)

Figure 8 is a magnetic density cloud diagram of a series transformer before and after DC bias suppression control. Therefore, it can be concluded more intuitively that the iron core saturation (i.e. DC bias) of the series transformer is effectively suppressed after the control module is added.

Figure 8. Series transformer magnetic density cloud
4. Conclusion
In this paper, the principle of DC bias problem of DVR series transformer is analysed. The suppression strategy of controlling the amplitude of the first half cycle of DVR output voltage is proposed. The correctness of the method is verified by Simpler, Matlab and Maxwell. The suppression strategy provides a good solution for the DC bias problem of series transformers in DVR, and has good engineering application prospects and theoretical reference value.

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