A Novel Control Strategy to Reduce Transformer Inrush Currents by Series Compensator

Juei-Lung Shyu
Department of Electrical Engineering,
Kao Yuan University
No.1821, Chung Shan Rd., Lu Chu Hsiang, Kaohsiung County 821
Taiwan R.O.C.
(Phone: +886-7-6077011; Fax: +886-7-6077009; E-mail: jlyu@cc.kyit.edu.tw)

Abstract — Inrush currents generated by unloaded power transformer often reduce power quality on the system. To improve this situation, this paper proposes an active inrush current compensator that is capable of reducing the inrush current effectively during startup mode. The proposed compensator is based on an inverter-based series compensator which is comprised of a single-phase inverter and series transformer. Voltage sags are very frequent events with energization of transformer or starting of large motors although their duration is very short. Hence, during voltage stabilizer mode, the existing series compensator is controlled by a voltage stabilizer controller and superimposes a compensating voltage on the inverter output whenever the load voltage deviate from the nominal value. This strategy is easier to implement because it requires no information of the transformer parameters, power-on angle of circuit breaker and measurement of residual flux. Some simulations results show satisfactory performance of the proposed technique on both inrush current reduction and correcting voltage sags.

Keywords: series compensator, transformer, inrush current, voltage sag.

I. INTRODUCTION

On the past several decades, inrush current phenomena generated from unloaded transformer have received much attention. Inrush currents are highly undesirable for some protective system, especially in high-tech industries. So, a few techniques of mitigating inrush currents have been proposed to limit the inrush currents. Generally, the transformer inrush currents are mainly determined by the power-on angle and the magnitude and direction of the original residual flux. To minimized these problems, controlled switch-on time of the circuit breaker or SCR firing angles have been proposed to suppress the start-up inrush current in power transformer [1]-[4]. However, it is difficult to measure instantaneous magnitude of residue flux and direction at the instant of transformer excitation. In addition, the spring force characteristics of circuit breaker also have a strong influence to determine the correct instant of mechanical closing time. Meanwhile, various statistical deviations in the characteristics of the circuit breaker may affect the success probability of this method. The authors have proposed a control strategy which the air gap thickness is controlled by an auxiliary winding inside a magnetic core of power transformer so that the inrush current can thus be reduced to a predetermined level [5]. But such transformer complex design will increase the cost of manufacturing power transformer and the auxiliary winding is redundant, when not operating in the startup mode.

In addition to the passive solutions mentioned above, this paper proposes an inverter-based series compensator using a current-mode control for reducing the undesired inrush current during startup mode. The series compensator injects a compensating current on the secondary winding of the series transformer. The compensating current supplied by the series compensator has opposite polarity to the inrush current produced by the power transformer. As a result, the inrush current is well suppressed with such a new control approach. In voltage stabilization mode, the series compensator injects the difference between the utility voltage and the desired load voltage through a series transformer to maintain the load voltage at the normal value. In summary, the inrush current reduction is incorporated as one of the main functions of the conventional series compensator without additional cost.

Thus, the proposed series compensator functions as inrush current suppression during startup mode and voltage sag compensation during voltage stabilization mode. Finally, the performance of the proposed series compensator will be validated by simulation results under various modes.

II. SYSTEM DESCRIPTION

A. Description of the circuit topology
Fig. 1. Circuit configuration of the proposed single-phase series compensator.

Fig. 1 shows the circuit configuration of the proposed single-phase series compensator. This configuration is based on a unified power quality controller [6]-[9]. The system consists of a series transformer connected in series with power transformer, voltage-source inverter and link inductor. The system has two operating modes. One is the startup mode and the other is the voltage stabilization mode. In startup mode as shown in Fig. 2, operation of the series compensator is modulated such that the compensation current is injected inversely to the series transformer. As a result, the startup inrush current is reduced considerably. The current $i_p$ in the primary winding of the series transformer is detected and multiplied by a reduction factor $k_R$ and turn ratio $n = n_s/n_p$ to get a current command $i_{inj}$ for reducing the inrush current. Then, the injected current $i_{inj}$ is obtained as

$$i_{inj} = -k_R \frac{n_p}{n_s} i_p$$  \hspace{1cm} (1)

$k_R$ can be set between 0 and 1, depending on the effective maximum reduction range of inrush current. As predicted, the control performance can be improved considerably with higher $k_R$.

Fig. 3 shows a basic configuration for modeling the ground fault of the series compensator during voltage stabilizer mode. It consists of a PWM inverter and voltage stabilizer controller. The impedance $Z_f$ connected to the PCC is used to create a single-phase fault. When voltage sags occur, magnitude of load voltage will drop below normal level because large fault current flow through $Z_f$. The PWM inverter which acts as a voltage-controlled voltage source is located after the series transformer and the injected voltage is serially added to the utility voltage. Based on the measurement of $V_f$, the voltage stabilizer controller will enable the series compensator generate the difference of the utility and load voltages, typically less than 20% of the rated voltage. The inverter operates only during a voltage sag condition and regulates the load voltage according to the desired PWM duty cycle determined from the controller.

Considering the equivalent circuit of the series transformer as shown in Fig. 4, the following voltage equations are given as

$$v_p = i_p r_p + L_p \frac{di_p}{dt} + (n-k_R)$$  \hspace{1cm} (2)

$$v_s = i_s r_s + L_s \frac{di_s}{dt} + \frac{1}{n} \frac{1}{k_R}$$  \hspace{1cm} (3)

From equation (2) and (3), the equivalent impedance in phasor form are expressed as

$$Z_p = (r_p + j \omega L_p) + j \frac{n-k_R}{n} \omega k_R l_m$$  \hspace{1cm} (4)
From equation (4) and (5), it shows that the equivalent impedance of the transformer is determined by the reduction factor $k_R$. In this case, the series transformer has low impedance at the fundamental frequency and high harmonic impedance to the $k$-th harmonics. Therefore, the series transformer greatly improves the equivalent impedance to limit the inrush current when power transformer is energized.

From the above, it can be seen that the proposed series compensator can function as inrush current suppression and achieve load voltage compensation, which is not achieved in a conventional series compensator.

### B. Control Strategy

Fig. 5(a) shows the basic block diagram of an inrush current controller. Assume the reference current and feedback current of the secondary winding are represented by $i_{inj}$ and $i_{inj}$, respectively. $k_p$ and $k_i$ are proportional and integral parameters of the PI controller, respectively. $k_{PWM}$ is a constant representing the gain of the voltage source inverter and is represented as

$$k_{PWM} = \frac{V_{DC}}{v_{tri}}$$

where $v_{tri}$ is the peak value of the triangular wave. From Fig.5(a), the closed-loop transfer function can be obtained as follows:

$$G_i(s) = \frac{i_{inj}}{i_{inj}^*} = \frac{(sk_p + k_i)s^2L_J + s(r_J + k_ppwm) + k_i}{s^2L_J + s(r_J + k_ppwm) + k_i}$$

When the parameters of the inrush current controller are properly chosen based on Bode-diagram method, the corresponding magnitude and phase of the transfer function can be close to

$$|G_i(s)| = 1 \quad \text{and} \quad \angle G_i(s) = 0$$

Note that the phase shift of the reference current and injected current is nearly zero, the injected current is nearly in phase with the primary winding current. Thus, the injected current $i_{inj}$ tracks the current command $i_{inj}^*$ closely while suppressing the startup inrush current.

Upon detection of voltage sag, the series compensator is switched immediately to voltage stabilizer mode. Fig. 5(b) shows the basic control block diagram of the voltage stabilizer controller. Required injected voltage is achieved by controlling the inverter output voltage. Let $v_L$ represents the nominal load voltage and $v_L$ represents the measured voltage on the load side of the series transformer. A voltage sag is present when $v_s$ is less than $v_L^*$. The objective is to regulate $v_L$ equal to $v_L^*$ when voltage sag is present. Assuming neglecting phase shift from $v_s$ to $v_L$, the magnitude of the load voltage $v_L$ is $v_L = v_s + v_{inj}$ and can further be simplified to

$$v_L = v_L^*(1 + \frac{n_p}{n_s}D)$$

where $D$ is a function of the PWM duty cycle which is essentially a variable pulse-width. The corresponding injected voltage $v_{inj}$ is given by the duty cycle $D$ as follows

$$v_{inj} = \frac{n_p}{n_s}V_{DC}D\sin\omega t$$

where $V_{DC}$ and $\omega$ are the DC bus voltage and angular frequency of the load voltage, respectively. Through closed-loop feedback, the duty cycle changes according to the degree of load voltage drop single-phase faults. A feed-forward path is added to the output of PI controller to get a fast dynamic response in the event of voltage sag. Parameters of $k_{pf}$, $k_{iv}$, and $k_{fo}$ are determined using Bode and root locus rules to meet the dynamic specifications. In order to obtain good load voltage regulation, the controller can precisely calculate the compensated series voltage $v_{inj}$ under fault conditions, and restore the load voltage to the accepted level with good dynamic response, especially in the presence of sensitive loads.
III. SIMULATION RESULTS

The proposed system has been simulated in order to verify feasibility. Fig. 6 to Fig. 14 show the simulations and comparisons of the proposed series compensator topology in both startup and voltage stabilization modes, where the utility voltage $V_L$; the inrush current $i_s$; the injected current $i_{inj}$; the flux $\phi$; the residual flux $\phi_o$; the power-on angle $\alpha$; the load voltage $V_L$; and compensated series voltage $V_{inj}$, respectively. The series compensator is operated at 5kHz switching frequency with $L_f = 3mH$, $v_{DC} = 950V$, and $v_s = 500V_{rms}$, $k_R = 0.8$, and $n_1/n_2 = 5$. All simulations are performed on the MATLAB/SIMULINK software platform. Both 10KVA power transformer and 1KVA series transformer are selected in the following results. Then, the simulation results of the inrush current are presented, in which the
power-on angle of the voltage and magnitude and polarity of residual flux are also taken into consideration. Fig.6. to Fig. 8. gives the results for power transformer energization when no series compensator is connected. It is shown that the power system contain transient inrush currents with amplitude up to 100A resulting from energization of unload transformer. Fig. 9 to Fig. 11 shows the waveforms of the inrush current when the series compensator is connected to the power system. It can be found that the proposed system can suppress the inrush current effectively under different magnitude and polarity of the residual flux conditions. Compared with Fig.6 to Fig. 11 it is indicated that the inrush current is reduced effectively because the series compensator limit the inrush current by injecting current inversely to the series transformer, Meanwhile, higher residual fluxes are rapidly attenuated within a cycle. Fig. 12 and Fig. 13 also numerically summary the simulation results for a residual flux \( \phi_p \) of -70%, 0%, +70% of peak normal flux and clearly demonstrate the effectiveness of the proposed active inrush current compensator. Therefore, significant reduction of start-up inrush current is achieved for any residual flux and power-on angles conditions.

In addition, the proposed system under voltage stabilizer mode is test. When the load voltage is decreased abruptly up to 25% with 50ms duration, the series compensator transfers instantly to the voltage stabilizer mode and keep the load voltage regulated as shown in Fig. 14. It shows that the load voltage is regulated by the voltage stabilizer controller and the series compensator injects compensation voltage to maintain the load voltage at normal level. Thus, the series compensator provides fast response to the voltage sag due to the ground fault.

**IV. CONCLUSIONS**

In this paper, an active method of the series compensator used for reduction of inrush current during startup mode is proposed. Its main features are simple and effective control strategy for the reduction of transformer inrush current. This strategy on the basis of the current injection by series compensator is quite different from the conventional approaches. This control strategy is easy to implement because the series compensator is effective in reduction of the startup inrush current for all power-on angles without prior measurement on residual flux in a transformer core. Simulation results are presented to verify the effectiveness of the proposed system for various operation parameters. The proposed system is simulated and the results demonstrate improvement in operating characteristics when compared with conventional approaches. It is shown that the proposed series compensator can suppress the inrush current effectively regardless of whether the transformer core has residual flux or not. Besides, the series compensator can inject compensation voltage to restore the load voltage to normal level for sensitive loads with fast response. Building an experimental prototype to verify the simulation results is required to prompt the proposed active inrush current compensator for practical application.
REFERENCES


