



Improving response to transient phenomena in coupling capacitive voltage transformers by thyristor devices

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ABSTRACT

Ferroresonance is a nonlinear oscillatory phenomenon that occurs under certain conditions. This investigation use an indicator of ferroresonance based on voltage for damping of dangerous overvoltages in coupling capacitor voltage transformers (CCVT). This paper investigates ferroresonance voltage for determination technical requirements of the ferroresonance suppression circuit (FSC) for detection and suppression of ferroresonance. In this technique, by using a back-to-back gated thyristor circuit, a damping resistance is switched to secondary side of the system transformer during dangerous oscillations. The control technique proposed in this paper is a “novel but classic” technique. The prediction of ferroresonance is achieved by detailed modeling using a digital computer transient analysis program such as the EMTP.

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Introduction

Power disturbances have become an important increasing factor throughout electrical networks. Ferroresonance is one of these disturbances that can occur on power systems, causing quality and security problems. Capacitive voltage transformers (CVTs) are widely used to provide voltage signals for measuring devices and protective relays. The dynamic performance of protective relays highly depends on the signals produced by the instrument transformers, and these signals depend on the overall transient response of the instrument transformers and the type of transients generated by the power system. The main disadvantage of capacitive voltage substations is their transient behavior. In other words, the major obstacle in using this electricity distribution technique is its transient characteristics. Ferroresonance and overvoltage transient problems could occur in these substations during different conditions.

Ferroresonance power supplies have played an important role in the power community for many years. These supplies have been utilized as a very reliable means of providing line voltage regulation. Ferroresonance is a particular type of oscillation, which can occur when a non-linear inductance is connected in series or parallel with a capacitance [1-3]. Ferroresonance does not occur regularly or predictably and this makes it very hard to analyze. Any response to a sudden change in the system can jump it out of a steady state and into ferroresonance.

All CVTs need to incorporate some kind of ferroresonance damping, because the capacitance in the voltage divider, in series with the inductance of the transformer and the series reactor, constitutes a tuned resonance circuit. This circuit can be brought into resonance by various disturbances in the network that may saturate the iron core of the transformer. This phenomenon can also overheat the electromagnetic unit or lead to insulation breakdown. Presently, Capacitive Coupled Voltage Transformers (CCVT's) with built in ferroresonance suppression circuits are the most widely used transformers in industry to suppress ferroresonance. This ferroresonance

suppression may be “passive” or “active” depending on whether the suppression circuit stores energy or not [4-6].

In this paper, by using power electronic devices a damper resistor is switched to the secondary side of the system transformer during dangerous oscillations. The basic design is a back-to-back gated thyristor circuit connected with a series resistance that is inserted in the transformer secondary. The purpose of this project is to design and construct a feedback control system to detect and dampen ferroresonant oscillations. The design is capable of controlling the amount of resistance inserted by implementing a power electronic circuit. The mitigation circuit employs a feedback control system which can determine an optimal operating point. Once detected, the power electronic circuit can be used as a variable resistance to be inserted into the circuit by varying the firing angle of the thyristors. This resistance dampens out the ferroresonance. Using the data for a coupling capacitive voltage transformer, a model is developed in this paper and occurrence of transient phenomena in different conditions can be simulated and analyzed by detailed modeling using a digital computer transient analysis program such as the EMTP. In this paper, FSC's has analyzed with EMTP.

The rest of this paper is organized as follows. Literature of related CCVT is reviewed in Section 2. Section 3 presents the ferroresonance in CCVT. In section 4, current ferroresonant dampening techniques and the FSC proposed are described, respectively. Control system for the F.S.C. proposed is shown in section 5. The simulation results of the FSC's performance are shown in section 6. This paper ends with a summary of conclusions.

Coupling capacitive voltage transformer

CCVT is a widely used apparatus for voltage measurement at transmission and subtransmission voltage levels. The output voltage of a CCVT is used for monitoring, protection relays and control applications. Proper design and tuning of CCVT components guarantee that its output is the required replica of the input (system voltage) under steady-state conditions. However, due to the CCVT energy storage elements and

magnetic saturation nonlinearity, its output waveform deviates from the input waveform during transients [7-8].

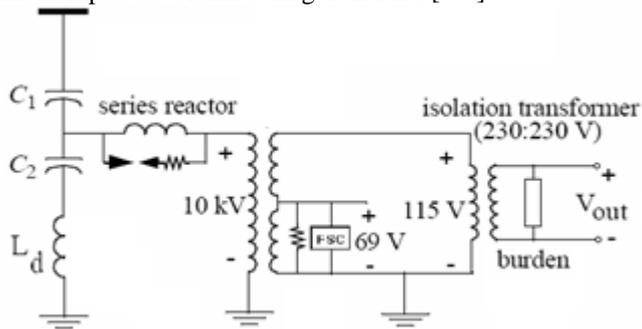


Fig.1- Capacitive coupled voltage transformer

A typical CCVT single line diagram is given in Fig. 1. Parameters vary widely between manufacturers and as a function of the voltage level. A complete set of data for a 161kV CCVT is given in [9]. Main components of a generic CCVT are: tuning reactor, step-down transformer (SDT), ferroresonance suppression circuit and a capacitive voltage divider. It consists also many additional devices which are not important in point of view transient's phenomena. As can be seen from Fig. 1 a CCVT is a favorable series ferroresonant circuit. C1 and C2 constitute a capacitive divider. L_d is drain coil which is used in Power Line Carrier (PLC) communications. The FSC block in Fig. 1 represents the ferroresonance suppression circuit.

Ferroresonance in CCVT

The CCVT shown in Fig. 1 is under study in this section. This is a CCVT 161kV with the rated output voltage of 115V. The knee point voltage of the CCVT SDT magnetization characteristic is assumed 3pu. To establish ferroresonance conditions, a resistor with the value of 0.05Ω is connected to the output of the CCVT for a period of about 0.1s and then it is disconnected. This results in occurrence of ferroresonance as shown in Fig. 2. In this case, FSC is not installed in the CCVT. The ferroresonance waveform has high peak amplitude of 5.12pu. To suppress the ferroresonance, effects of proposed method is investigated.

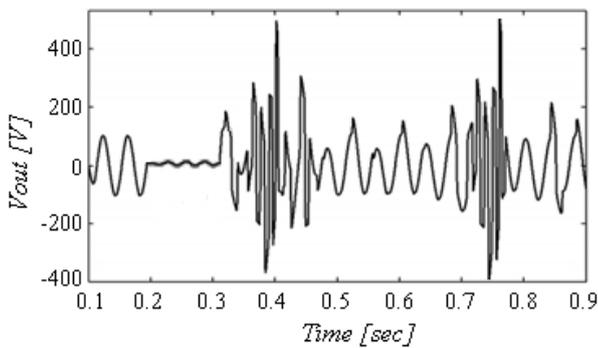


Fig.2- CCVT ferroresonance without FSC

Current ferroresonant dampening techniques

A ferroresonance suppression circuit is designed to prevent subsynchronous oscillations. They appear when there is saturation of the core of a step-down transformer during overvoltage conditions. This section presents techniques for ferroresonance mitigation by installing of a damping resistor at the secondary side of the transformer. This circuit has significant impact on the characteristic of the CVT transients because it creates an extra path (apart from the burden) for dissipating energy. We can categorize ferroresonance suppression circuits as "Active" and "Passive".

Active ferroresonance suppression circuits (AFSC)

As can be seen from Fig. 3.a - 3.c, the circuit consists of a parallel LC combination. This filter which is connected in parallel with the burden, blocks fundamental frequency from the filter load and passes other frequencies to the load to be damped. Since ferroresonance is always accompanied by some harmonic components, the filter presents additional load to the CVT to damp out the phenomenon. R_f is the filter load and C_f and L_f are the capacitance and inductance of the filter which should be tuned to the fundamental frequency. In circuit (a) inductance L_f is a tapped reactor which results in two coupled inductances. In circuits (b) and (c) L_f is a simple inductance and the inductance of transformer, respectively.

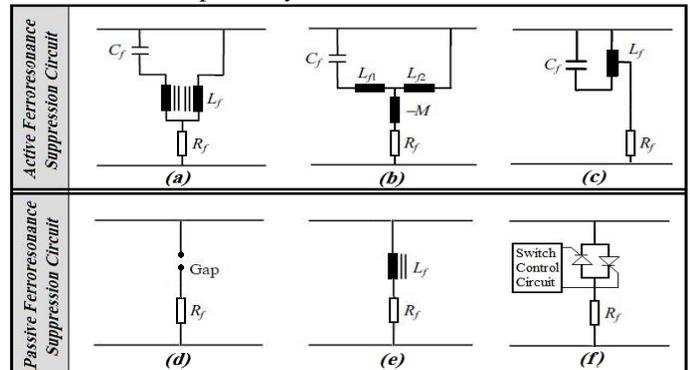


Fig.3- Active and reactive ferroresonance suppression circuits

Passive ferroresonance suppression circuits (PFSC)

This circuit has a loading resistor (R_f) and an air gap loading resistor R permanently connected. Under normal system conditions, the secondary voltage is not high enough for the gap to flash, therefore, the loading resistor has no effect. If a ferroresonance condition occurs, the gap will flash over and the loading resistor will attenuate the oscillation (dissipate the energy) (Fig. 3.d).

A second approach is to add voltage sensitive load. If voltage increases above normal, a saturable reactor effectively adds more load. Studies also show that ferroresonance suppression RL circuit with saturable reactor has little effect on the CVT transients [10]. The saturable inductor (L_f) is designed to saturate at approximately 140% of nominal voltage (Fig. 3.e).

Proposed passive FSC

A new technique to damp dangerous overvoltages is proposed and evaluated in this paper. In this technique, by using power electronic devices a damper resistor is switched to the secondary side of transformer, when it is necessary. For designing the desired FSC, the following points should be considered:

- When the amplitude of overvoltages is more than a threshold, the firing pulses must be issued to switch-on the damping resistor. For implementation of this point, the voltage amplitude is obtained using a resistive divider circuit. This signal should be compared to the maximum threshold voltage.
- The damping resistor should be switched-off when the load is reconnected to system.
- Power electronic switches go to off mode in negative half cycle of voltage but the damping resistor should be connected continuously to secondary side of the transformer during the whole period of overvoltages.

Hence, the switches should be arranged in inverse parallel model. Fig. 3.f shows the basic design of the FSC is two back to back thyristors (SCR's) in series with a damping resistance.

Both thyristors in the schematic share the same gate signal from a pulse generator. If a source is connected across the terminals of the FSC then the current passing through the

damping resistor can be controlled. Current conduction is determined by the firing angle, which in turn is controlled by the input to the gates of the thyristors.

In Fig. 4 notice how current conduction through the dampening resistance of the FSC is controlled for different firing angles at the gate signal. The waveform shown in the Fig. 4 is for the chopped current waveform passed through the damping resistance. The chopped waveform is shown in black and the points of firing are indicated with arrows. This waveform is ideal and neglects any transients caused by the thyristors switching the path through the resistance on and off. The waveform is displayed for two cycles.

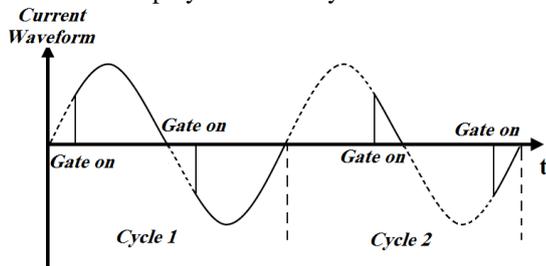


Fig.4- Chopped current waveform from firing thyristors

The maximum system voltage threshold for starting the firing pulses is chosen 1.4pu. In addition, the simulation results represent that if ferroresonance overvoltages are fully damped and the load is reconnected to the system, the amplitude of system voltage would decrease to lower than 0.9pu. For this reason the minimum voltage threshold to issue the off mode pluses can be taken as 0.9pu. GTO and IGBT are appropriate switches in this application, because, the switch-on threshold voltage (1.4pu) and switch-off threshold voltage (0.9pu) are not the same.

Frequency response's ferroresonance suppression circuits

The type of suppression ferroresonance device i.e., "Active" or "Passive" can have a significant response on the transient response of the CCVT. Various types of FSCs have different effects on frequency response of CVTs and in some conditions can cause significant errors in measured signals. In the case of measurement of rapid changes in the system voltage or measurement of harmonics, the overall frequency characteristic of the CVT must be taken into account. In order to obtain the frequency response data to be used as input data to the routine developed to compute the linear CCVT parameters, frequency response measurements, for magnitude and phase, were carried out for mentioned before CCVT, from 10 Hz to 10 kHz.

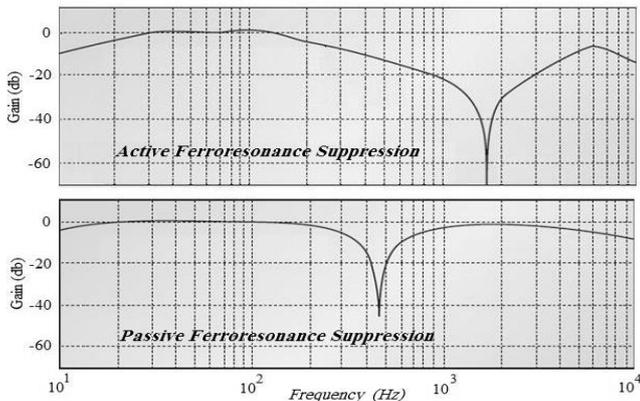


Fig.5- Active and reactive ferroresonance suppression circuits' frequency response

A type of ferroresonance suppression circuits is power frequency blocking filter. The characteristic of the CVT under study equipped with this filter is shown in Fig. 5. The top plot in Figure 5 shows the frequency response of a CVT with an AFSC.

Ideally, the frequency response should be a flat line at 0 dB, which means the CVT passes all frequency components without attenuation. Passing all frequency components makes the CVT output voltage a close representation of its input voltage. If the frequency response shows attenuation at different frequencies, the CVT behaves much like a filter and introduces transients and time delay. Furthermore, in power systems including power electronics converters such as HVDC and/or FACTS equipments, switching devices produce higher order harmonics. In such systems, using RL ferroresonance suppressor in CVTs is preferable. Fig. 5 shows the frequency response of the CVT with a PFSC. Notice that this frequency response is much flatter than the one shown in Figure 5.

Control system for the F.S.C. proposed

In choosing a method of detection for the ferroresonance suppression circuit, the indicators for onset of ferroresonance must first be considered. High over-currents and over-voltages are also an indicator of ferroresonance. In addition to these, ferroresonance may produce considerable noise (from magnetic forces stressing the core) and may increase transformer temperature (due to ohmic losses in the windings caused by over-currents). Any of these indicators are possible candidates to be utilized as a method of detection. The voltage during ferroresonance also exceeds its rating. Knowledge of this behavior may be used to indicate the onset of ferroresonance. By using some type of comparator current or voltage could simply be compared to their expected values. If the expected value is exceeded then this could detect that a ferroresonant event has occurred. Here, we use an indicator of ferroresonance based on voltage.

From an input and output standpoint the ferroresonant suppression circuit has essentially two main functions. First of all it is required to detect ferroresonant oscillations and then begin switching in a resistance paralleled with the transformer secondary. This is to dampen the ferroresonant oscillations as quickly as possible. The second function is to employ a feedback control system that ensures ferroresonance is damped.

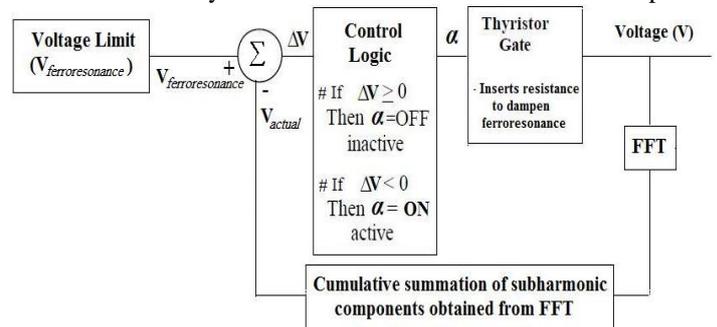


Fig.6- Detection, dampen and feedback of ferroresonance control system

For mentioned requirements, the control system diagram displayed in Fig. 6 can be used. The system shown in the diagram represents the required operation of the F.S.C. when detecting if a ferroresonant event has occurred. Voltage is used as the input signal for detecting ferroresonant oscillations. The value for the voltage limit ($V_{ferroresonant}$) has been determined experimentally ($V_{ferroresonance} = 0.4 * V_n$). V_n is equal to the maximum value of voltage waveform when the system is operating in a normal state (i.e. not ferroresonant).

After completing a ferroresonance on the CCVT, the waveforms of voltage was analyzed using the harmonic components were broken down using a Fast Fourier Transform (FFT). From the cumulative summation of subharmonic

components the average voltage (V_{actual}) in the transformer was computed ($V_{actual} = \sum_k V(t_k^*)$, $k = \text{subharmonic components}$). The V_{actual} signal is calculated over some set interval of time and is then subtracted from a $V_{ferroresonant}$ pre-programmed in memory. This determines signal ΔV ($\Delta V = V_{ferroresonance} - V_{actual}$).

This signal ΔV is the input to the control logic module of the control system. If the input ΔV is a positive quantity then this means that the voltage limit has not been exceeded and the firing mechanism remains inactive. If ΔV is a negative quantity then the control logic switches the firing mechanism into an active mode. Firing angle alpha (α) is initially fired at a low angle to insert the largest amount of resistance at the start of ferroresonance.

After the detection control system has been activated, the feedback control system is required to satisfy the second function of finding that ensures ferroresonance is damped. In the feedback path voltage is again sampled to integrate in order to obtain a measurement for voltage V_{actual} . The same process as used in the detection control system is used here again. This process is then cycled back through the feedback and the control system process is continued.

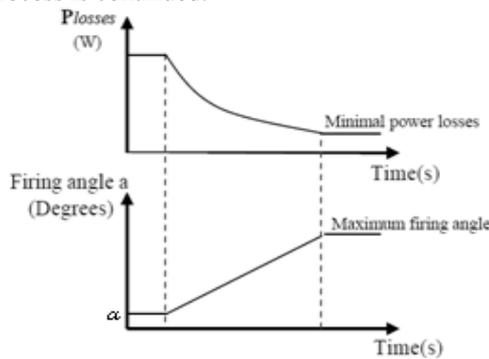


Fig.7- Theorized Relationship between Power Losses in F.S.C. and Firing Angle α

The power losses in the F.S.C. are directly related to the amount of current allowed passage through the damping resistance. These losses are $P=RI^2$ losses. The amount of current allowed to pass is determined by the firing angle α . Fig. 7 shows relationship between power losses in F.S.C. and firing angle α . The ferroresonant oscillations are initially dampened from firing at $\alpha=5$. This will insert maximum losses and therefore dampen resonant oscillations as quickly as possible. It is important to dampen quickly for protection the transformer from damage. If the ferroresonance is kept under control then the firing angle will be increased by every cycle of the control system. As the system increases firing angle linearly with time expectations are to see the power ($P=RI^2$) losses reducing at some non-linear rate of decay.

Simulation results of the FSC’s performance

In this section, some simulation tests are provided to highlight the usefulness of the proposed FSC. To suppress the ferroresonance, effects of proposed method into CCVT output voltage during ferroresonance conditions and damping out the phenomenon (with different damping resistor) are investigated and simulated.

Fig. 8 shows the effect of proposed FSC with damping resistor on damping out ferroresonance. When this load resistor is $R_f = 30\Omega$, ferroresonance is eliminated within 0.2s. During this period, the CCVT sustains high magnitude overvoltages. As depicted in Fig.9, Using lower resistance, ferroresonance is more effectively damped out. However, there is an optimum

resistance by which the best suppression is obtained. With an optimum $R_f = 10\Omega$, ferroresonance is suppressed within 2-3 cycles. By decreasing R_f value to 5Ω , the damping time increases and the response is more oscillatory (Fig.10).

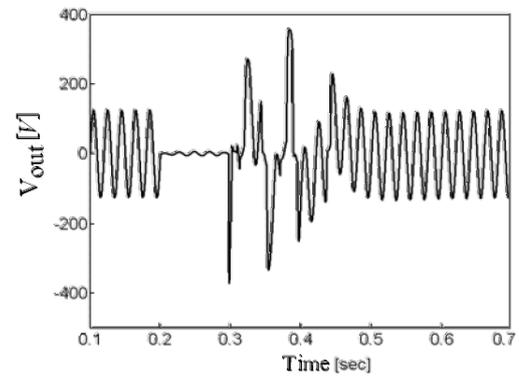


Fig.8 Damping ferroresonance in presence of FSC with $R_f = 30\Omega$

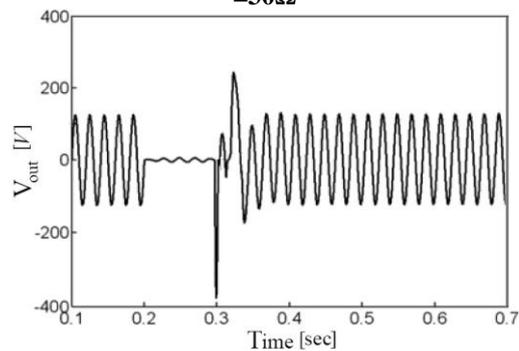


Fig.9 Damping ferroresonance in presence of FSC with $R_f = 10\Omega$

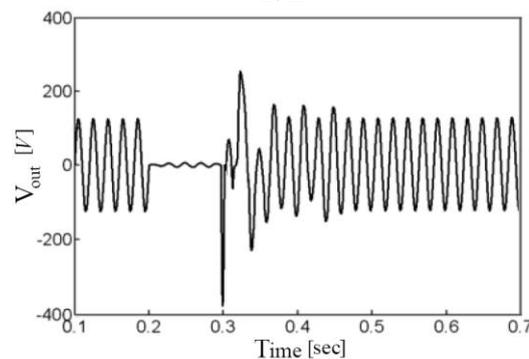


Fig. 10 - Damping ferroresonance in presence of FSC with $R_f = 5\Omega$

Conclusion

Ferroresonance is the phenomena that can produce overvoltage; the violence may be enough to damage some equipment, so recognition of Ferroresonance phenomenon has a special importance. Nowadays this phenomenon is increasingly found because the capacitive voltage or potential transformers, low loss, and underground cable, high capacitance, are generally used. A novel method for suppression of ferroresonance in coupling capacitor voltage transformers presented in this paper. In this technique, by using a back-to-back gated thyristor circuit, a damping resistance is switched to secondary side of the system transformer during dangerous oscillations. Simulation results show that the proposed procedure is efficient in identifying and mitigating of ferroresonance (Ferroresonance is effectively cleared within two cycles).

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