Mitigating Ferroresonance in Coupling Capacitor Voltage Transformers With Ferroresonance Suppressing Circuits

Saeed Shahabi, *Electrical Engineering Department*, *Iran University of Science & Technology,* Davood Babazadeh, *Energy Engineering Department, Sharif University of Technology*, Rasul Esmaeilnia Shirvani, *Islamic Azad University of Saveh*, Mohammad Purrezagholi, *Babol University of Technology*

***Abstract*— In order to restrain ferroresonance in coupling capacitor voltage transformers (CCVT), two kinds of ferroresonance suppression circuits (FSCs) , are proposed in this paper: the resonant type, the fast-saturation reactor type which are connected to secondary side of CCVTs. Frequency domain analyses, for voltage ratio magnitude, are carried out for CCVTs to obtain preferable FSC. Furthermore, using surge suppressors such as metal oxide varistors (MOV) to improve the performance of the FSCs is investigated. Time domain simulations demonstrate that ferroresonance can be cleared in few cycles in presence of FSCs. The Electromagnetic Transients Program (EMTP) is used for modeling and fine-tuning the FSCs.**

***Index Terms*— CCVT, Ferroresonance, FSC, Frequency Response Characteristic.**

I. INTRODUCTION

Coupling capacitor voltage transformers (CCVT) are widely used in power systems as input sources to protective relays and measuring and control instruments. Protective relays can be affected by the transient response of CCVT which can cause malfunction in the protective devices of the electric power system. Proper design and tuning of CCVT components assure that its output is the required replica of the input (system voltage) under steady-state conditions. However, due to the nonlinearity of the iron cores of compensating reactor and step-down transformer, its output waveform deviates from the input waveform during transients. The phenomenon of ferroresonance is a particular concern during transients, and can cause noticeable deviation of CCVT response from the actual input waveform [1,2,3].

In order to restrain ferroresonance, we connect a ferroresonance suppression circuit (FSC) to the secondary side of the CCVT. There are two kinds of ferroresonance suppression circuits (FSCs): 1) the fast-saturation reactor type, 2) the resonant type, categorized according to different principles. Fast-saturation reactor type and resonant type dampers are currently dominating the market. Thus, when resonance occurs, resistance in the damper will be immediately connected into the loop to consume the resonance energy before the intermediate transformer saturates, so that ferroresonance can be restrained [3,4].

In this paper, the Trench TEHMP161A CCVT is used for the studies. The Electromagnetic Transients Program (EMTP) is used for modeling and fine-tuning the FSCs. Time domain simulations demonstrate that ferroresonance can be cleared in few cycles using each type of FSC and overvoltage protective device.

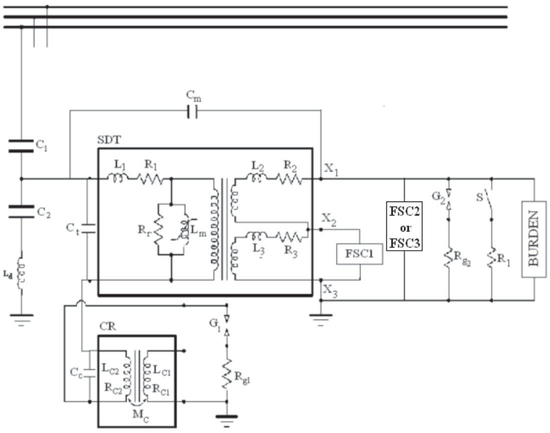


Fig.1. CCVT schematic diagram.

II. CCVT MODELING

Schematic diagram of the Trench TEHMP161A CCVT used for the studies is shown in Fig. 1 [1]. FSC1 is the active ferroresonance circuit and FSC2 represents the passive ferroresonance suppression circuit and FSC3 is power electronic device for damping overvoltage.

The CCVT composed of capacitive voltage divider (C_1 and C_2), drain coil (L_d), stray capacitances (C_m, C_t and C_c), step down transformer (SDT), compensating reactor (CR), overvoltage protection device G and its series resistor Rg and ferroresonance suppression circuits (FSC1 or FSC2).

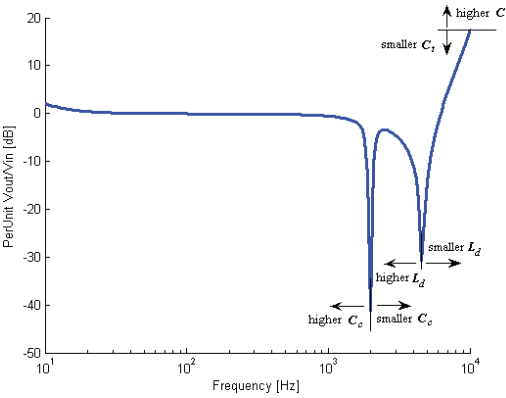


Fig.2. Sensitivity analysis of the CCVT voltage ratio magnitude.

In order to reduce the complexity of the CCVT model, it was carried out a sensitivity analysis in frequency-domain to detect the most important model parameters [1,6,7].

In this work the sensitivity analysis was made by varying the values of the parameters previously known in litreture for 138 KV CCVT and observing the frequency response curves of the magnitude for the CCVT voltage ratio.

Fig.2 shows the sensitivity of the CCVT voltage ratio magnitude with respect to some of the most important parameters.

Fig.2 demonstrates that the stray capacitances of the compensating inductor (C_c) , the primary winding (C_t) and the drain coil (L_d) which is used in power line carrier (PLC) communications are very important in high frequencies.

The sensitivity analysis results have shown that the parameters C_m, R_2, L_2, R_3 and L_3 have not a large influence on the CCVT frequency response [6].

As a result of the sensitivity analysis, the CCVT model was reduced to a model, shown in Fig.3.

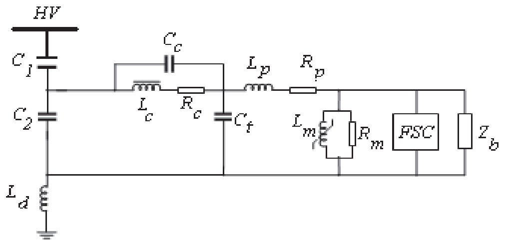


FIG.3. CCVT MODEL

III.FERRORESONANCE SUPPRESSION CIRCUITS

We have studied two effective ferroresonance suppression circuit(FSC) in this paper which could damp out ferroresonance better than the others.

A. *Fast-saturation reactor type*

One suppression concept is to add voltage sensitive load. It means that if voltage increase above normal, a saturable reactor effectively adds more load. The current through the reactor is negligible unless the ferroresonance is present. So the only ferroresonance suppression circuit component affecting the transient response is loading resistor [8].

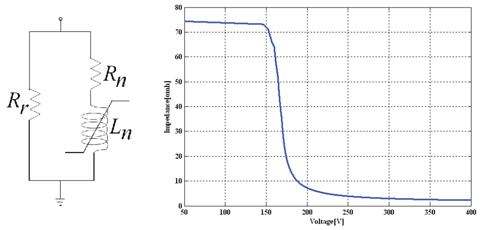


Fig.4. Schematic diagram and impedance vs. voltage characteristic curve of saturable reactor

Fig.4 shows the schematic diagram and suitable characteristic curve of this ferroresonance suppression circuit (FSC1). FSC1 consists of a saturable reactor (*Rn* and *Ln*) in parallel with permanent load *Rr*.

Saturation reactor has the magnetization curve shown in Fig.5. Ln has a knee point at about 150% of rated voltage. As shown in this figure, an increase in voltage more than 150% of the rated voltage causes *Ln* to reduce. So magnitude of total impedance of FSC1 decreases.

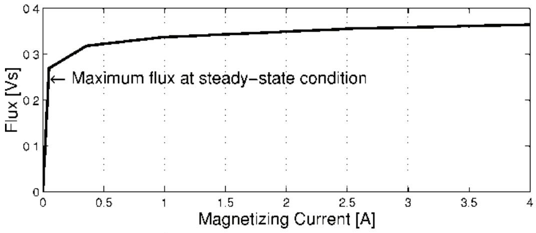
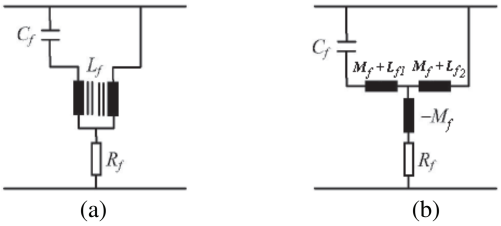


Fig.5. Magnetization curve of *Ln*

B. *Resonance type*

This circuit is a serial-parallel RLC filter (FSC2) consisting of two inductors (L_{f1} and L_{f2}) which are mutually coupled to each other, a capacitor *Cf* and a resistor R_f, is tuned to the fundamental frequency with a high Q factor. So it can pass frequencies around the fundamental frequency.The damping resistor R_f is used to attenuate ferroresonance oscillations.



(a) (b)

Fig.6. Ferroresonance suppression circuit (FSC2):
a) Ferroresonance filter – b) Mathematical equivalent circuit of filter.

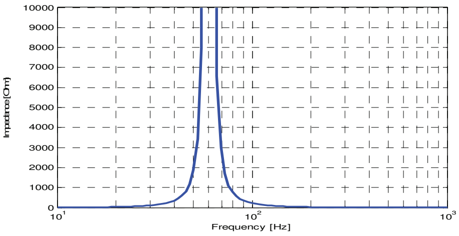


Fig.7. Impedance frequency characteristic of FSC2

The desired filter should act as an open-circuit in the rated frequency. So,

$$1 - \omega_0^2 C_f (L_{f1} + L_{f2} + 2M_f) = 0 \qquad (2)$$

By considering equation (2) we assume that

$$a = \omega_0^2 C_f (L_{f1} + M_f) \qquad (3a)$$

$$b = \omega_0^2 C_f (L_{f2} + M_f) \qquad (3b)$$

For $\omega \geq 2\omega_0$, the amplitude of $|Z(j\omega)|$ should be less than a threshold value *(Zt)*, therefore we have

$$|Z(j\omega)| \leq Z_t \qquad (4)$$

To obtain a filter which can damp ferroresonance overvoltages in a short duration, Zt is chosen equal to the rated value of system load, i.e

$$|Z(j\omega)| \leq Z_n = \frac{V_0^2}{S_n} = 33.0625\Omega \qquad (5)$$

$$\Rightarrow |Im(Z(j\omega))| \leq 33.0625$$

From equation (1) we have

$$|Im(Z(j\omega))| = n\omega_0 \left| \frac{b(1-n^2a)}{C_f\omega_0^2(1-n^2)} - M_f \right| \qquad (6)$$

Assuming

$$f(n) = \frac{an^2-1}{n^2-1} = \frac{a-\frac{1}{n^2}}{1-\frac{1}{n^2}} \quad ; n = \frac{\omega}{\omega_0} \qquad (7)$$

For enough large values of *n* we can estimate *f(n)=a* and inequality (6) leads to

$$\left| \frac{ab}{C_f\omega_0^2} - M_f \right| \leq \frac{33.0625}{n\omega_0} \qquad (8)$$

For large values of *n,* the right-hand side of inequality (8) would lead to zero. To satisfy (8) for large values of *n*, the left-hand side of the inequality should be chosen equal to zero, therefore

$$\frac{ab}{C_f\omega_0^2} - M_f = 0 \qquad (9)$$

So by setting $b = \frac{M_f C_f \omega_0^2}{a}$ in (6), we have

$$\left|1 - \frac{1}{a}\right| \leq \frac{(n^2-1) \times 33.0625}{nM_f\omega_0} \qquad (10)$$

The right-hand side of (10) is a rising function with respect to n and its minimum is obtained for n = 2. To satisfy (10) for all values of n, the left-hand side of (10) should be smaller than the minimum of the right-hand side, i.e.

$$\left|1 - \frac{1}{a}\right| \leq \frac{3 \times 33.0625}{2 \times M_f\omega_0} = \frac{0.13155}{M_f}$$

$$\Rightarrow \; 1 \leq \frac{1}{a} \leq 1 + \frac{\beta}{M_f}, \quad \beta = 0.13155$$

So we could assume that

$$\frac{1}{\mathrm{a}} = 1 + \frac{\beta}{M_f} \qquad (11)$$

Therefore

$$b = \frac{\beta}{\beta + M_f}, \qquad C_f = \frac{\beta}{\omega_0^2(M_f+\beta)^2} \qquad (12)$$

And by using equation (3a,b), we obtain

$$L_{f1} = \frac{M_f^2}{\beta}, \qquad L_{f2} = \beta \qquad (13)$$

Parameter M_f of this filter could be selected to achieve a desirable performance for the filter. The larger the value of parameter M_f, the smaller the filter capacitance that is obtained. By assuming $M_f = 2\beta$ we obtain

$$M_f = 0.2631H, C_f = 5.943\mu F$$
$$, L_{f1} = 0.5262H, L_{f2} = 0.13155H \qquad (14)$$

The FSC2 admittance based on its model shown in Fig.6(b) is

$$Y_f(s) = \frac{1 + A_1s^2}{B_0 + B_1s + B_2s^2 + B_3s^3} \qquad (15)$$

Where, $A_1 = C_f(L_{f1} + 2M_f + L_{f2})$, $B_0 = R_f$, $B_1 = L_{f2}$, $B_2 = R_fC_f(L_{f1} + 2M_f + L_{f2})$, $B_3 = C_f(L_{f1}+M_f)(L_{f2}+M_f) - M_fC_f(L_{f1} + 2M_f + L_{f2})$.

Replacing the FSC2 parameters by their calculated values, it is obtained two imaginary zeroes, $z_1 = j377$ and $z_2 = -j377$, and two real poles, $p_1 = -79.38$ and $p_2 = -1790.28$ [9].

All poles are located on the left half-plane of the s plane so there is no numerical instability in the CCVT secondary voltage waveform.

The value of R_f should be chosen lower than burden value. Using higher values for R_f, ferroresonance overvoltage could not be damped effectively [10].

IV. FREQUENCY RESPONSE CHARACTERISTICS OF CCVTS WITH FERRORESONANCE SUPPRESSION CIRCUITS

Fig. 8 shows the frequency characteristic of the CCVT with fast-saturable reactor as a FSC1. The resonance frequency of this CCVT which corresponds to the tuning reactor and its stray capacitance is around *2 kHz*. Second resonance frequency is due to the drain coil. The frequency response is almost flat up to *2 kHz*. It means that to measure a voltage signal having frequency components up to *2 kHz*, no compensation is needed. However, the CCVT damps frequency components in the range *2 kHz* and *6 kHz* and magnifies the components beyond *6 kHz*.

Another type of ferroresonance suppression circuits is a resonance type such as power frequency blocking filter. The characteristic of the CCVT under study equipped with this filter is shown in Fig. 9. Due to damping effect of the filter, the frequency response of the CCVT is not flat and all frequency components of the measured signal, except the frequencies around the fundamental, are attenuated. Therefore, the output of this CCVT for measuring voltages with rapid changes or with higher order harmonic contents is not reliable and this may result in overreach in distance relays. So using RL ferroresonance suppressor in CCVTs is preferable[7].

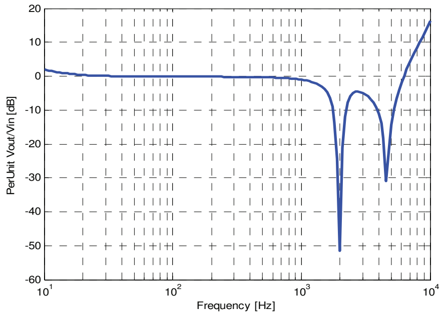


Fig.8. Frequency response characteristic of CCVT with saturable reactor as ferroresonance suppressor

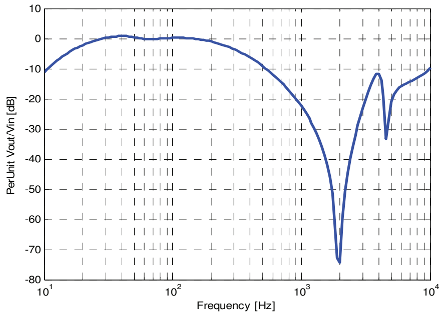


Fig.9. Frequency response characteristic of CCVT with resonance filter as ferroresonance suppressor

V. SIMULATION RESULTS

Simulations using EMTP-RV have been carried out to test the effectiveness of introduced FSCs on fast suppression of phenomenon of ferroresonance and also on transient response of CCVT. The CCVT ferroresonance response is investigated under the following conditions. Initially switch S is open and burden is a series R_L branch which consumes 1VA at $115V_{RMS}$ and lagging power factor of 0.85. To establish ferroresonance conditions, switch S is closed ($R_L=30m\Omega$) and after approximately seven cycles opened. Opening S saturates SDT and results in ferroresonance [1,7]. Ferroresonance overvoltage on secondary side of CCVT without any FSCs and overvoltage protection device is shown in Fig.10. A 350 Vrms surge arrester (ZnO) is used in this study.

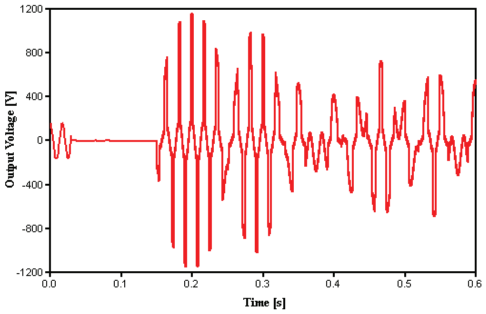
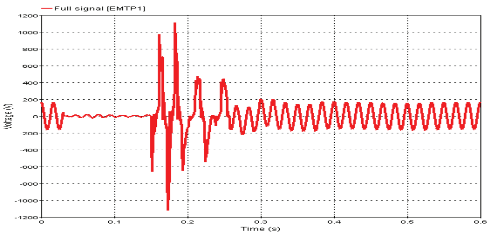


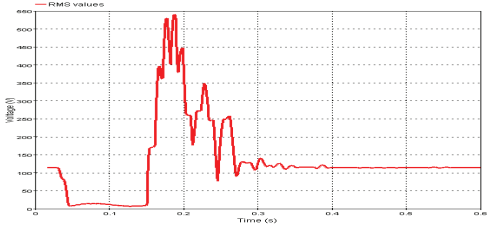
Fig.10. CCVT secondary side voltage without any FSCs and overvoltage protection device.

A. *Performance of the fast-saturation reactor type*

This ferroresonance suppressing circuit consists of resistor $R_r=75\Omega$ in parallel with the saturable reactor. Filter reactor has the magnetization curve shown in Fig. 2 and the internal resistance of $R_n=1.35\Omega$ because Fig.11 shows that the phenomenon of ferroresonance is readily damped out within $0.2s$ when $R_n=1.35\Omega$. It should be noted that increasing R_n beyond a certain value reduces the effectiveness of L_n. Simulation results of the voltage on secondary side of CCVT and effects of FSC1 and overvoltage protection device are shown in Fig.13. As shown in Fig.11 FSC1 can damp out ferroresonance. Therefore with overvoltage protective device such as ZnO surge arrester in presence of FSC1 (Fig.12), ferroresonance overvoltage suppression is improved and damped within $0.05s$.

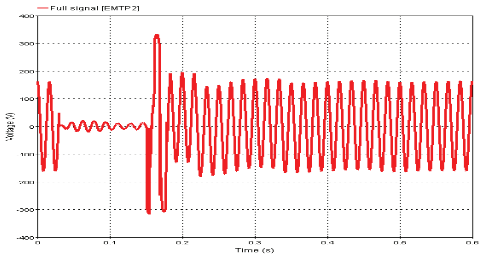


Full signal

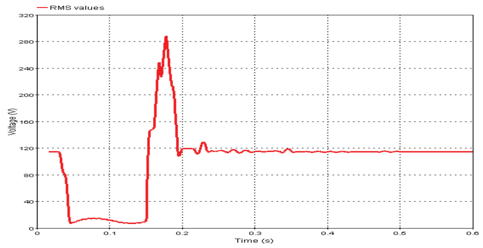


RMS values

Fig.11. CCVT response to ferroresonance and damping out the phenomenon using saturable reactor with $R_n=1.35\Omega$

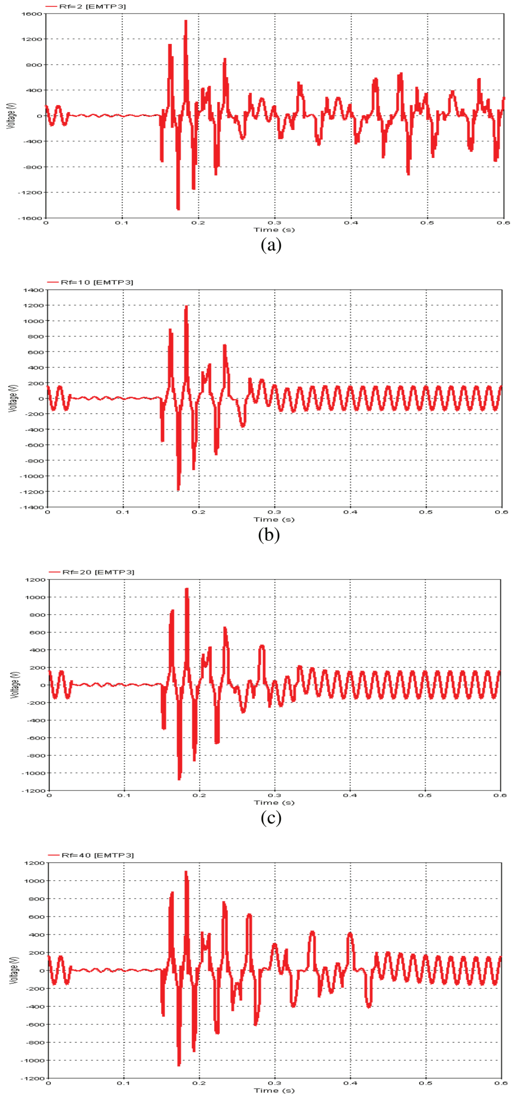


Full signal



RMS values

Fig.12. Influences of surge arrester in presence of FSC1 on ferroresonance overvoltage suppression



(a)

(b)

(c)

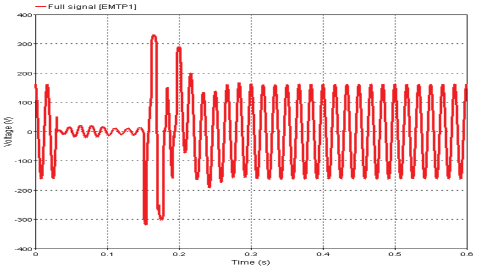
(d)

Fig.13. CCVT response to ferroresonance using fundamental frequency blocking filter with *a)*$R_f=2\Omega$*, b)*$R_f=10\Omega$*, c)*$R_f=20\Omega$*, d)*$R_f=40\Omega$

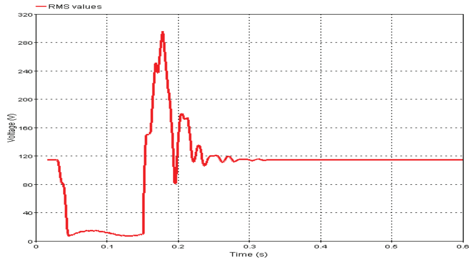
B. *Performance of the resonance type*

In this section, some simulation tests are provided to highlight usefulness of the filter which is mentioned before.Fig. 12 shows the case in which a ferroresonance filter with different damping resistor is installed in the CCVT. When this load resistor is $Rf=2\Omega$, ferroresonance is not eliminated. During this period, the CCVT sustains high magnitude overvoltages. As depicted in figure 14(b)&(c), using higher resistance, ferroresonance is more effectively damped out but we should pay attention that by increasing Rf value more than specific value , the damping time increases more and the response is more oscillatory. So the optimum value by which the best suppression is obtained within *0.15s* is $R_f=10\Omega$ because by increasing Rf value to 40Ω, the damping time increases as shown in Fig.13.

Fig.14 depicts full signals and rms values of ferroresonance response of CCVT by using optimum value of R_f (10Ω) in active suppression circuit (FSC2) in presence of ZnO. In Fig.15, simulation test using FSC2 and overvoltage protective device together, shows that ferroresonance overvoltages are eliminated in fewer cycles and damping time of active suppression circuit (FSC2) is lower than FSC1. Therefore FSC2 has a better effect on clearing of ferroresonance in presence of arresters than FSC1.



Full signal



RMS values

Fig.14. Influences of surge arrester in presence of FSC2 on ferroresonance overvoltage suppression

VI. CONCLUSIONS

In this paper, various ferroresonance suppression methods have been reviewed and their performances have been investigated. Three main FSCs used in CVTs are fast-saturation reactor, resonance blocking filter and power electronic device. Additional devices such as surge arresters may be added to improve the performance of the FSCs.

Frequency response characteristic of CCVT with saturable reactor indicates that the errors of magnitude of voltage ratios are very small in contrast to resonance filter. This because resonance filter adversely affects the frequency response of the CVT and results in erroneous output signal in the case of rapid changes or higher order harmonics in the system voltage. As a result, the saturable reactor is a more desirable solution.

On the other hand, time domain simulation results show that filter, saturable reactor and thyristors can appropriately damp out ferroresonance within a few cycles. However, during the first cycle, the CVT experiences a high overvoltage which can not be suppressed by these three techniques. As a solution, adding a surge arrester can limit the overvoltage and significantly reduce the damping time. Also, the comparison between RMS values of these techniques have shown that electronic devices such as two back to back thyristors with damping resistance have more influences on damping out ferroresonance than the others.

APPENDIX

Table I. Trench Tehmp161A CCVT Technical Data

Rated primary voltage	98 kV
Rated secondary voltage	49.29 V
Rated tertiary voltage	65.71 V
Rated burden	400 VA

Table II. SDT Magnetization Curve Data

Current (A)	Flux (Vs)
0.007425	123.79
0.018562	129.59
0.074246	136.45
0.222739	137.82

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