Capacitive Voltage Substations Ferroresonance Prevention Using Power Electronic Devices

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***Abstract* – This paper describes the underlying theory and model of capacitive voltage substations and its assosiated problems. This system is intended to supply electricity to rural communities directly from high voltage transmission lines. This technique leads to important cost reductions when compared with conventional alternatives. However, in several transient cases, some problems such as ferroresonance and overvoltages can occur in these substations. These transient cases are simulated in this paper and a new technique is proposed for damping of dangerous overvoltages due to ferroresonance. In this technique, by using power electronic devices, a damping resistance is switched to secondary side of the system transformer, when necessary. Several computer simulation tests are presented in the paper to highlight the usefulness of this technique. The simulation results present that overvoltages are adequately limited.**

***Keywords* –** Power system, Transients, Capacitive substations, Ferroresonance, FSC.

I. INTRODUCTION

The development of sparsely populated areas results in the extension of electrical transmission networks to remote and rural communities as well as industries such as mines, ore processing, forest products and secondary industries such as tourism. The capacitive divider technique has been known for quite a while but using this technology to transform high voltage to medium voltage for delivering power to remote areas is more recent. With this technique, energy is drawn from the electric field of the high voltage transmission line by use of discrete capacitors.

This technique leads to important cost reduction when compared with more conventional electromagnetic coupling systems, e.g. high voltage power transformers [1]. However, 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.

Using the data for a real capacitive substation, a model is developed in this paper and occurrence of transient phenomena in different system conditions such as short circuit, system energization with and without the connection of load, and load rejection are simulated and analyzed. Computer simulation tests are performed to represent the system behavior in transient cases. Result of simulations represent that some transient cases lead to dangerous overvoltages, which can damage the instruments and system insulations.

A new technique to damp dangerous overvoltages is proposed and evaluated in the paper. By using power electronic devices a damper resistor is switched to the secondary side of the system transformer during dangerous oscillations. In the paper, firing pulses preparation procedure, power electronic control algorithm and designing method of the desired circuits are described. The usefulness of this model is tested by various simulations. Details of the system modeling and proposed technique are described in the paper.

II. THEORY

A. Model

The principles of capacitive – coupling transformers are not new, as they have long been used both by manufacturers of the capacitor voltage transformers required by electrical utilities and by some electric utilities for feeding small loads [2,3], so only a brief review is presented here. Fig. 1 shows the capacitive substation circuit model and Fig. 2 shows the Thevenin equivalent of the voltage divider (C_1 and C_2) seen from the load side. The Thevenin equivalent voltage of the divider V_{th} is

$$V_{th} = \frac{C_1}{C_1 + C_2} \bullet V_{in} \qquad (1)$$

and its impedance is that of capacitors C_1 and C_2 in parallel, i.e. $C_{th} = C_1 + C_2$.

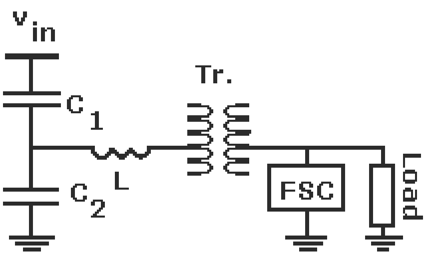

Fig. 1 Model of capacitive substation

The FSC block in Fig. 1 represents the ferroresonance suppression circuit.

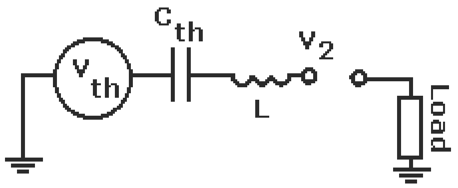

Fig. 2 Equivalent Thevenin circuit seen from the load side

An inductor L is added to the capacitive voltage divider to cancel the Thevenin impedance C_{th} at 50 Hz. This regulation is done by adjusting C_1 , C_2 and L so they satisfy:

$$LC\omega^2 = 1 \qquad (2)$$

where $\omega = 2\pi 50$ rad/seconds

Since the impedance is zero at 50 Hz, the output voltage V_2 remains equal to and in phase with V_{th}, which in turn V_{th} is proportional to and in phase with V_{in}, whether the load be resistive, capacitive or inductive.

B. Ferroresonance

If capacitive-coupling technique is used as a substation for feeding remote loads or for rural electrification, it normally includes distribution transformers installed on the outgoing feeders. It is possible that these transformer cores get saturated in some transient cases and interaction of their saturated core and capacitive divider may result in ferroresonance. Active and passive ferroresonance suppression circuits (FSCs) are proposed in the literature to damp ferroresonance oscillations.

Different methods exist for analyzing ferroresonance oscillations [4,5]. One of these methods is outlined as follows.

Let us have an analytical view of the problem at fundamental frequency. Transformer voltage-current phasor relationship as well as the Thevenin equipment source load line is shown in Fig. 3. It can be seen that there are three possible solutions of which ***A*** and ***C*** are stable. Solution ***A*** is the normal linear solution of the capacitive substation system. In case of some transients such as an output short circuit or upon system energization, solutions ***B*** or ***C*** may be reached instead, and therefore ferroresonance is experienced.

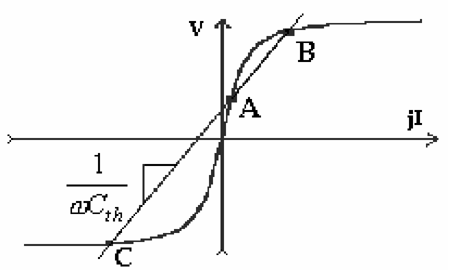

Fig. 3. Analytical view of ferroresonance problem

C. Model development

Using the data for a real capacitive substation, a model is developed and simulated in this paper. EMTDC and MATLAB softwares are used to develop the model. Occurrence of ferroresonance in different system conditions such as short circuit, system energization and load rejection are simulated and analyzed using this model.

A capacitive substation with the service capacity of 1650 KVA three phase and components data included in Table 1, as introduced in reference [1] is used for this study. System load is assumed to be pure ohmic and is modeled by a resistor. The transformer saturation behavior is built from the voltage- current curve given by reference [6].

Table 1. List of data in model

V_{in}	V_o	C_1	C_2	L	Trans. Ratio	S_{3phase}
161KV (L-L)	380V (L-L)	0.98μF	5.34μF	1.6H	25KV/380V	1650 KVA

III. Simulation of Transient Cases

Using the capacitive substation model, many different simulation studies are performed and performance of the model was evaluated. Obtained results are similar to what is reported in the literature, so the model accuracy is satisfactory.

Through different simulations, it was observed that in some transient cases, dangerous ferroresonance overvoltages occur. These critical cases are outlined below.

A. Energization behavior

One of the most critical operating conditions is energization, while there is no-load present at the output. The test results shown in Fig. 4, reflects this condition. Fig. 4 presents the voltage of transformer primary side, when the system is energized at no-load. Ferroresonance phenomenon is observed in the voltage signal and the associated overvoltages can damage the instruments or system insulation.

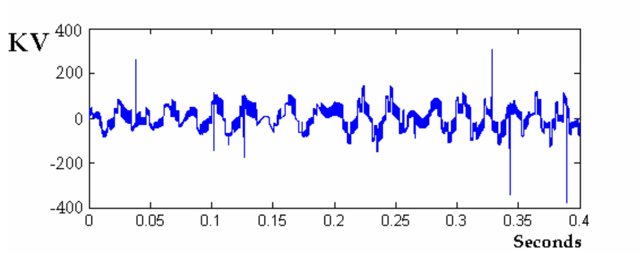

Fig. 4. Transformer primary side voltage at no-load energization

The results of different simulations indicate that the occurrence of ferroresonance in this situation depends on conditions such as:

- The residual fluxes circulating in the core of the transformer before its energization,
- The closing instants of the circuit breaker which initiates the energization of system or the initial angle of the input voltage,
- The type of transformer winding connection,
- The switching sequence of system energization such as single phase switching or three phase simultaneous switching.

Various simulation studies are performed for different combinations of the station design parameters and system switchings. It is shown that in most cases, some dangerous overvoltages occur. Common ferroresonance suppression methods like three phase simultaneous switching can not prevent these dangerous transients. Therefore, it is necessary to find out a method to suppress these phenomena.

B. Short circuit behavior

Rejection of load before the clearance of a temporary short circuit fault is one of the most critical conditions of ferroresonance occurrence. Dangerous overvoltages do not occur during the time of fault period because the voltage is decreased when the fault is occurred. In contrast, after the clearance of a temporary fault the system voltage could increase and lead to ferroresonance.

The overvoltages due to ferroresonance could be damped by resistance of system load (Fig. 5).

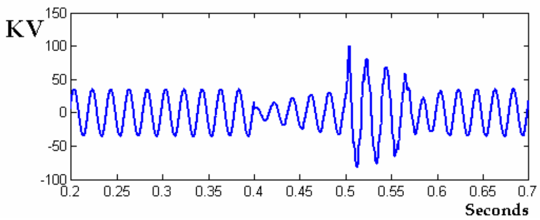

Fig. 5. Damping of ferroresonance overvoltages in temporary short circuit by system load resistance

In contrast, ferroresonance lead to dangerous overvoltages, when the load is rejected before the clearance of fault. Fig. 6 represents the primary side voltage of the transformer when a single phase (phase *A*) short circuit occurs at *0.4s*. Phase *A* voltage is shown in this figure. This fault is cleared after 0.1 seconds and the load is rejected by protection system during the fault period. In this case ferroresoance overvoltages are observed clearely.

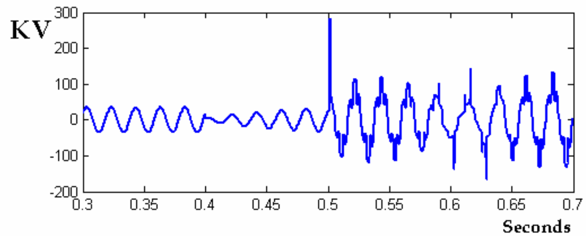

Fig. 6. Primary voltage ferroresonance for temporary short circuit with load rejection

C. Response to load on/off

It was shown that the rejection of load during occurrence of a fault leads to ferroresonance overvoltages. It is also interesting to see how the system responds to loads being shut off and on. Fig. 7 shows the output voltage when the load is disconnected and connected at the transformer output. At the time the load is disconnected at *0.4 s*, the output voltage is seen to be increased because of ferroresonanc. When the load is re-connected at *0.5 s*, the output voltage returns to its normal case. It should be noted that the disconnection of load for three phase switching as well as single phase switching leads to ferroresonance overvoltages.

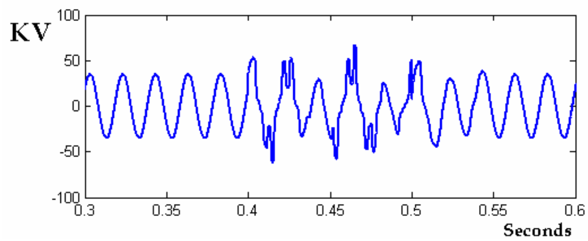

Fig. 7. Response to load off/on.

IV. FERRORESONANCE SUPPRESSION METHOD

Simulation results represented that in different system conditions such as short circuit, system energization at no-load and load on/off the ferroresonance overvoltages occur. This problem is the major obstacle in using this optimal rural electrification technique. Hence, it is necessary to find out a method to damp the ferroresonance overvoltages.

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 are 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. 8 shows the FSC circuit with schematic view of the related control circuit.

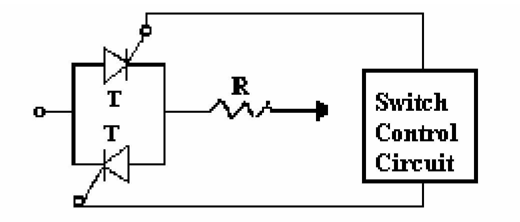

Fig. 8. FSC with inverse-parallel model switches

Through different simulation experiments, it was found that a damping resistor in the range of system rated load, leads to satisfactory results while it does not have high power losses.

The maximum system voltage threshold for starting the firing pulses is chosen 1.4 pu. 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 0.9 pu. For this reason the minimum voltage threshold to issue the off-mode pluses can be taken as 0.9 pu. GTO and IGBT are appropriate switches in this application, because, the switch-on threshold voltage (1.4 pu.) and switch-off threshold voltage (0.9 pu.) are not the same.

V. Simulation Test By Using FSC

In this section, some simulation tests are provided to highlight the usefulness of the proposed FSC. Transient cases such as system energization in no-load, temporary short circuits and load on/off are simulated again by using the proposed FSC.

A. No- load energization

As illustrated in Fig. 4, the energization of capacitive substation at no-load, is one of the most critical cases that faces to dangerous ferroresonance. The ability of the proposed FSC in damping the no-load energization overvoltages is tested in this section.

Fig. 9 shows the primary side voltage as well as current through damping resistor in the case of system energization for three phase simultaneous switching. The breaker which initiates energization, closes at $t = 0.3$ *s*. After the detection of overvoltages with amplitude more than maximum threshold, the firing pulse generator circuit issues the pulses at $t = 0.375$ *s* so that, the FSC causes the system voltage to return to its normal case at $t=0.46$ *s*. After some time, a timer is activated to connect load to the system, and then causes the damping resistor to be removed. If connection of load to the system is not possible, the system control circuit shut downs the entire substation. Various simulations of system energization for other types of switching sequences and various amounts of relevant parameters mentioned in subsection III were performed. Through these studies, it was found that the proposed FSC can adequately damp the ferroresonance in the case of system energization.

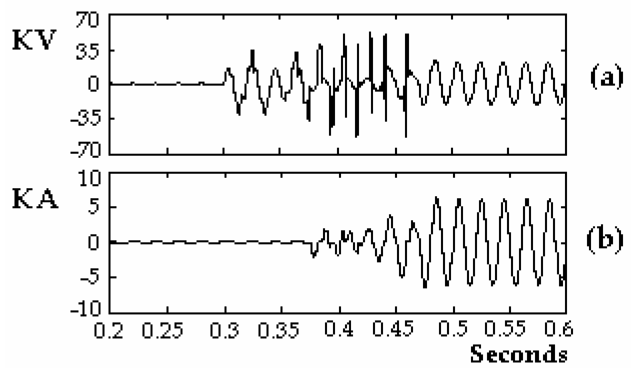

Fig. 9. System voltage in energizing with FSC (a) and current through FSC (b)

B. Temporary short circuit

To evaluate the proposed FSC ability, it is also examined in the case of temporary faults at the output or primary side of the transformer. All types of short circuits are simulated and usefulness of the proposed FSC is proven.

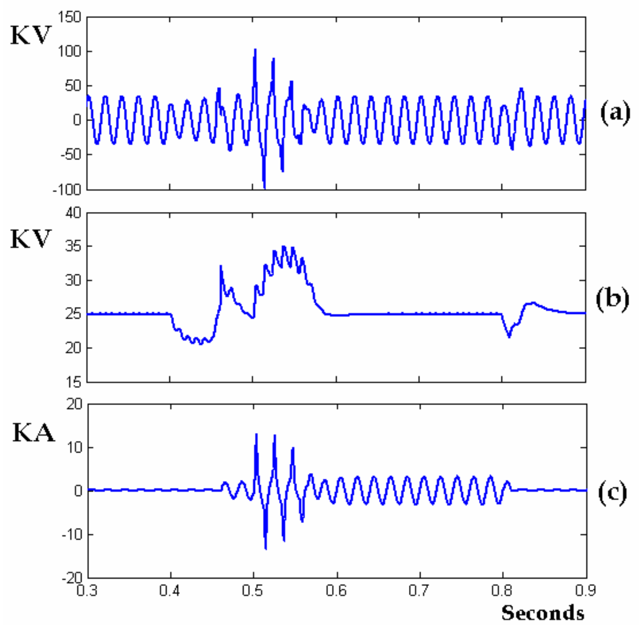

Fig. 10. Damping of ferroresonance in temporary short circuits

For example, Fig. 10a shows the system voltage when a single-phase fault is applied at phase *A*. This fault is cleared after *0.1 s*. The substation protection device has removed the load *0.05 s* before the clearance of the fault. The overvoltages due to ferroresonance are damped by FSC in a short time period. Fig. 10b shows the measured rms value of system voltage and Fig. 10c shows the current through the damping resistor.

Comparison of Fig. 10a with Fig. 6, reveals the effectiveness of the proposed FSC.

It should be added that a timer is used in substation control system to control the duration of using damping resistor in the circuit. About 200 ms after damping of overvoltages, the timer issues a signal to the load to reconnect the system, if possible or causes the protection system to disconnect the entire substation. When load is reconnected to the substation, the rms value of voltage goes down to lower than the minimum threshold and the off-mode pulses are issued to disconnect the FSC from the system. This procedure is shown in Figures 10b and 10c. Therefore, The maximum thermal rating of the damping resistor can be obtained as follows:

$$W = K \frac{V_{max}^2}{R} t \quad (3)$$

Where:

'W' is thermal rating of the damping resistor,
'K' is safety margin and assumed to be 1.1,
'V_{max}' is the maximum voltage appeared on FSC and assumed to be 1.5 pu.,
'R' is FSC's damping resistor,
't' is the maximum duration of continuous usage of damping resistor and assumed to be 400 ms.

The maximum thermal rating of damping resistor in this application is about 500 K.Watt.Sec.

C. Response to load on/off

At the end, the ability of proposed FSC is tested in damping the transient overvoltages of load on/off case. In this case, the new technique leads to very good results when compared with other conventional FSC's [1]. Fig. 11 shows the system voltage, when the load is disconnected and reconnected at the transformer output. At the time the load is disconnected, the overvoltages due to ferroresonance are produced but immediately the FSC is activated and controls the ferroresonance. As Fig. 11 illustrates the system load is disconnected at $t = 0.4$ s. The resulted overvoltages are damped in less than *0.04 s*. This load is reconnected at $t = 0.5$ s. Fig. 11b shows the rms value of primary side voltage. The overvoltages and undervoltages due to these phenomena are clearly represented in this figure. The current through the FSC damping resistor is also represented in Fig. 11c.

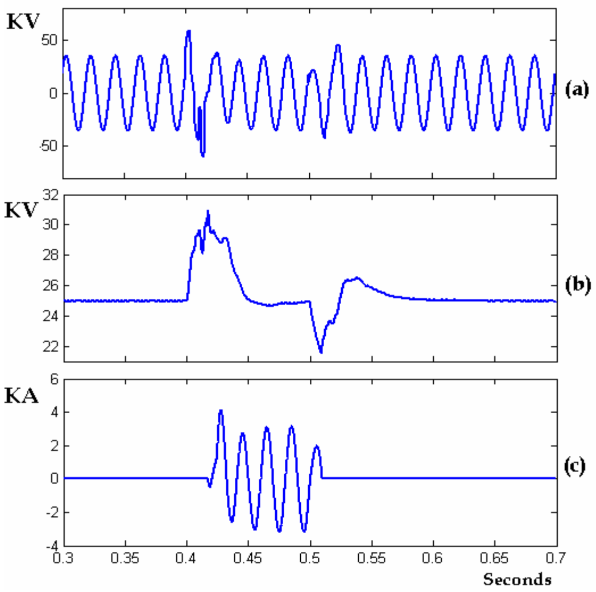

Fig. 11. Damping of ferroresonance in load on/off

Comparison between Fig. 11 and Fig. 7 shows the effectiveness of the proposed FSC in suppression of ferroresonance and its dangerous overvoltages.

VI. Conclusion

The system of capacitive substation which is intended to supply electricity to rural communities does not require a costly power transformer and leads to major cost reduction. In contrast, the problem of ferroresonance is the major obstacle of using this technique. In this paper a reliable method to suppress the transient overvoltages of ferroresonance is offered. The ability of this technique is tested in transient cases in which the dangerous overvoltage can occur. Obtained simulation results prove the usefulness of the proposed method.

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