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Switching Transient Analysis Of Capacitor Coupled Substation

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***Abstract*— Capacitor Coupled Substation is one of the low-cost technology for rural electrification (RE). However, the basic component of CCS is a capacitor and switching on the CCS during energisation process can result in an unwanted, high-frequency inrush current and transient overvoltage. These transients can lower the lifetime of CCS and can damage the electromagnetic switches such as circuit breakers. This paper, therefore, presents switching transient analysis of capacitor-coupled substation (CCS). Firstly, a CCS is modelled and simulated using MATLAB/Simulink. Transient response of the CCS with and without Ferro-resonance circuit is investigated. Secondly, a prototype of CCS was constructed, and the same investigation was done.**

Among many observations, it was generally observed through simulation and practical results that the tapping voltage oscillates when Ferro-resonance circuit is not incorporated

Keywords*— *Capacitor Coupled Substation, Resonance, transient, Rural electrification

I. Introduction

Literature indicated that more than 1.6 billion people, mostly in developing countries, do not have access to electricity and that most of them live in rural areas [1] [2]. The various un-conventional rural electrification (URE) technologies that have been identified and explored in various literatures are as follows:

- Single Wire Earth Return (SWER) [3] [4],
- Shielded Wire Schemes (SWSs) [5],
- Voltage transformers (ASVTs) [6], [7] and
- Capacitor Coupled Substation.

This URE sub-station technology offers significant opportunities for reduction of construction, operating and maintenance costs of grid-based rural electrification. This Grid-based electricity offers a cheaper option for lighting and small appliances usage in rural settlements [8].

Capacitor coupled substation technology is originated from the concept of capacitive divider technique to transform high voltage to medium voltage for delivering electric power to remote areas. With this technique, energy is drawn from electric field of high voltage transmission line by use of discrete capacitors. When compared with the conventional electromagnetic circuit, this technique leads to significant cost reduction [9]. However, since the fundamental component of CCS is a capacitor, switching on the CCS during energisation process can result in an unwanted, high-frequency inrush current and transient overvoltage. These transients can lower the lifetime of CCS and can damage the electromagnetic switches such as circuit breakers. This paper, therefore, presents an analysis of switching transient of a capacitor-coupled substation. In this paper, results of a MATLAB/Simulink model and a practical prototype are presented.

II. Mathematical Modeling

Figure 1 shows the basic single-line diagram of a Capacitor Coupled Substation. Transient response characteristics depend on two factors [10]:

- The coupling capacitor value
- Ferro-resonance – Suppression circuit design

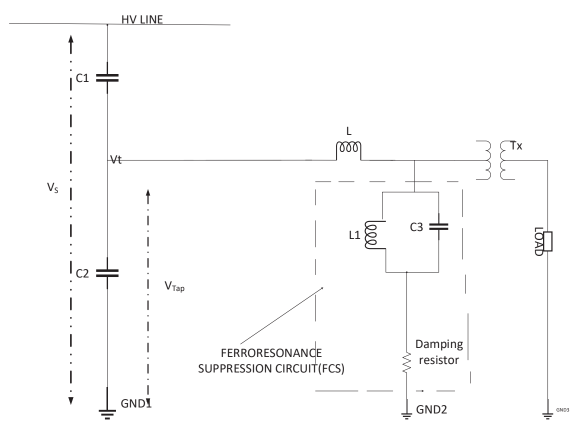

Fig 1 Single line diagram of a CCS [10]

A. *The coupling capacitor value*

A CCS is made of a number of capacitor units connected in series. The number of capacitor units depends on the applied primary voltage level. Two values represent the CCS capacitance: one for the equivalent capacitance above the intermediate voltage point (C_1) and the other for the intermediate capacitance below the intermediate voltage point (C_2). High capacitance value in a CCS decreases the CCS transient magnitude. However, increasing the CCS capacitance value can increase the CCS cost but decreases the

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CCS transient response. Hence, design engineers must strike a balance between CCS performance and cost [10] [11].

B. Ferro-resonance suppression circuit design

Ferro-resonance sometimes called nonlinear resonance is a type of resonance which occurs when a circuit containing a nonlinear inductance is fed from a source that has series capacitance, and the circuit is subjected to a disturbance such as the opening of a switch.

In CCS construction, Ferro-resonance circuit (FRC) is incorporated to suppress any nonlinear resonance called Ferro-resonance. Two types of Ferro-resonance suppression circuit are active and passive Ferro-resonance.

Active Ferro-resonance suppression circuits (AFSC) consists of an LC parallel tuning circuit with a loading resistor. The LC tuning circuit resonates at the system frequency and presents a high impedance voltage to the fundamental voltage. For frequencies above or below the fundamental frequency, the LC parallel resonant impedance gradually reduces to the resistance of the loading resistor and attenuates the energy off-nominal-frequency voltage [12].

Passive Ferro-resonance suppression circuits (PFSC) have permanently connected saturable inductor, loading resistor and an air-gap loading resistor. Once a Ferro-resonance oscillation exists, the induced voltage flashes over the gap and shunts in the loading resistance, to attenuate the oscillation energy [12].

C. Capacitor selection

Capacitors are chosen in such a way that C_1 is smaller than C_2 by a factor that can give the desired voltage level at the output [13] , [14]. With V_s and V_{Tap} being the supply voltage and Tap voltage (reduced voltage) respectively and the impedances of the capacitance C_1 and C_2 being Z_1 and Z_2, voltage ratio as a function of the divider impedances or capacitance is written as:

$$V_{tap} = \frac{Z_2}{Z_1+Z_2} V_s = \frac{C_1}{C_1+C_2} V_s \qquad (1)$$

The coefficient $\frac{Z_2}{Z_1+Z_2}$ is the transformation ratio of the system.

The conditions for selection of C_1 and C_2 are detailed in [14].

The FSC block in figure 1 represents the Ferro-resonance suppression circuit. The FSC comprises of a capacitor C_3, an inductor L_1 connected in parallel and a damping resistor R connected in series. Values of capacitor C_3, inductance L_1 and R are calculated as follows [15]:

$$C_f = C_3 = C_{th} = C_1 + C_2 \qquad (2)$$

$$L_1 = L_f \leq \frac{1}{(2\pi f)^2 C_f} \qquad (3)$$

$$3\sqrt{L/C} < R < \left(\frac{2}{3}\right)\sqrt{\frac{L}{C}} \qquad (4)$$

III. Simulation Case Study And Results

This section covers MATLAB/Simulink model of CCS used for the case study. The parameters used for simulation are as follows:

Transformer rating 1 KVA, Capacitor C_1 = 0.375µF, Capacitor C_2 = 3.075µF, Vs=240V, Inductor L = 3 H, Primary side of Transformer= 525 V, Secondary side of Transformer= 220V, Damping resistor = 4.4 kΩ, Load = 2 kΩ

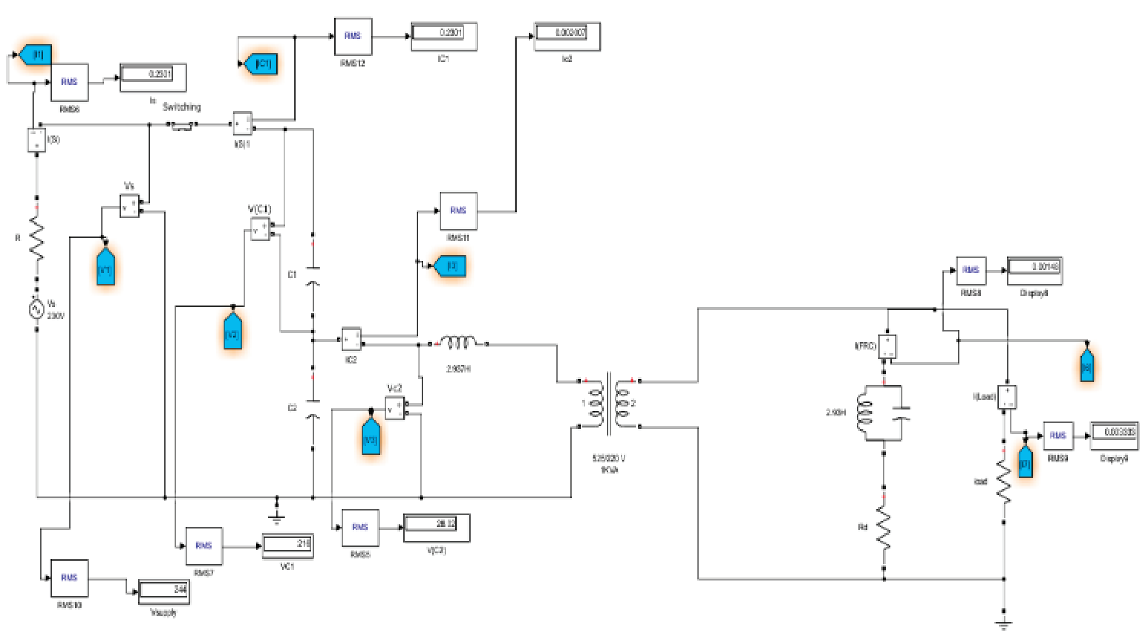

Fig 2 MATLAB/Simulink model of for CCS

A. CCS with FRC and No Load

A disturbance is initiated by switching of the CCS from supply at 0.3 seconds and switched it back to supply at 0.4 seconds. Figure 3 shows the current and voltage I_S and V_S at the point of connection. It can be seen that the Supply Voltage remains stable and the current does not show any inrush when the CCS is switched back on. This shows that the FRC suppresses inrush current.

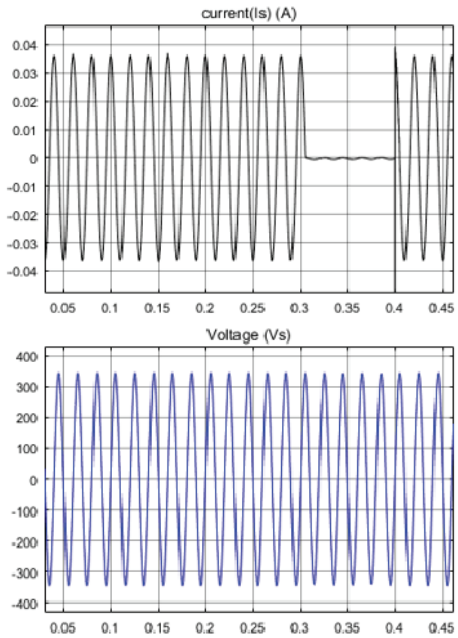

Fig 3 CCS with FRC at No Load: V_S and I_S

Fig 4 shows the voltage and current V_{C1} and $I_{C1,}$ respectively. It can be seen that V_{C1} and I_{C1} remained stable after the disturbance.

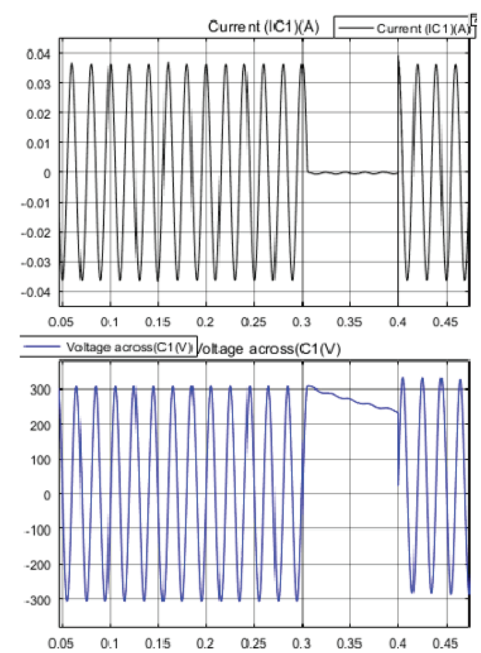

Fig 4 CCS with FRC at No Load: V_{C1} and I_{C1}

Fig 5 shows the voltage and current V_{C2} and $I_{C2,}$ respectively. It can be seen that V_{C2} discharges to zero during the disturbance, oscillates and stabilised in about 0.2 seconds. The current I_{C2} fluctuates and stabilise after 0.2 seconds.

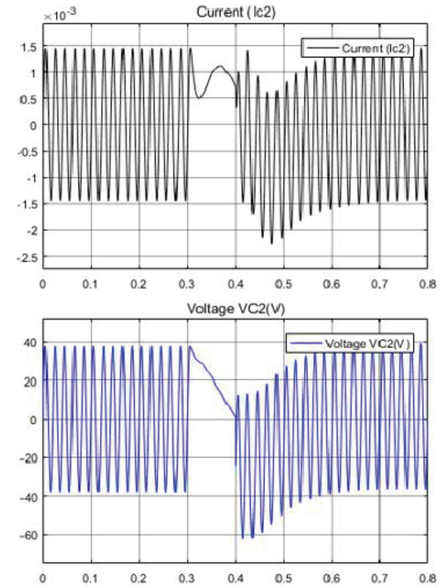

Fig 5 CCS with FRC at No Load: V_{C2} and I_{C2}

B. CCS with No FRC and No Load

At this case, the CCS is simulated without an FRC. A disturbance is initiated at 0.3 seconds, which lasted for 0.1 seconds, and power returns at 0.4 seconds.

Figure 6 shows the supply current I_S and voltage V_S at the point of connection. It can be seen that the Supply Voltage remains stable, but the current I_S gives a high inrush current when the CCS is switched back on. Comparing this current with that of figure 3 shows that the FRC is working effectively.

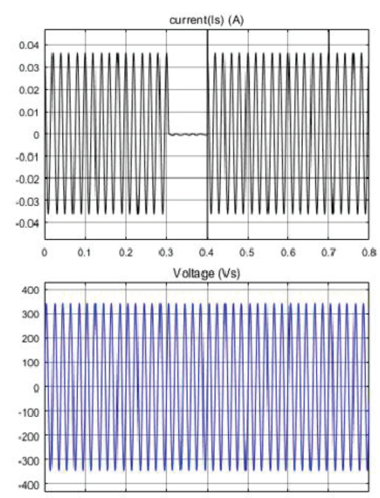

Fig 6 CCS with no FRC at No Load: V_S and I_S

Fig 7 shows the voltage and current V_{C1} and I_{C1}, respectively. It can be seen that V_{C1} stabilises after the disturbance and current I_{C1} gave a half cycle of inrush current and settled quickly.

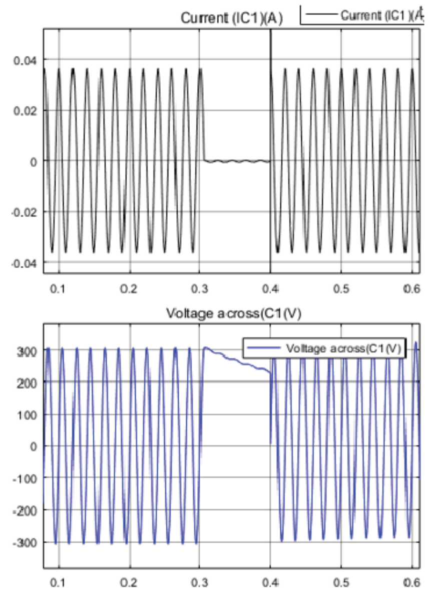

Fig 7 CCS No FRC at No-Load: V_{C1} and I_{C1}

Fig 8 shows the voltage and current V_{C2} and I_{C2}, respectively. It can be seen that V_{C2} is unstable and oscillates after the disturbance. The current I_{C2} gives a very high inrush current and continues to fluctuate. Therefore, the FRC circuit is critical in CCS technology, and care must be taken in the selection of the components of FRC for transient stability of CCS.

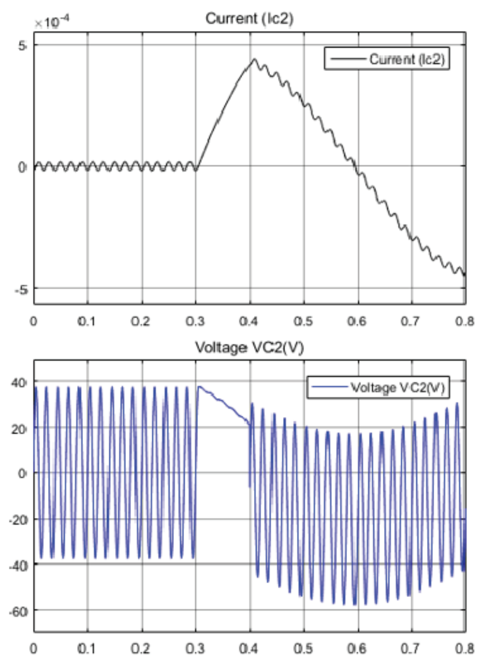

Fig 8 CCS with No FRC at No-Load: V_{C2} and I_{C2}

IV. EXPERIMENTAL SETUP

In order to verify the simulation work, a small prototype of CCS is constructed. Figure 9 shows the experimental prototype, which was developed to verify the concept and the simulation results.

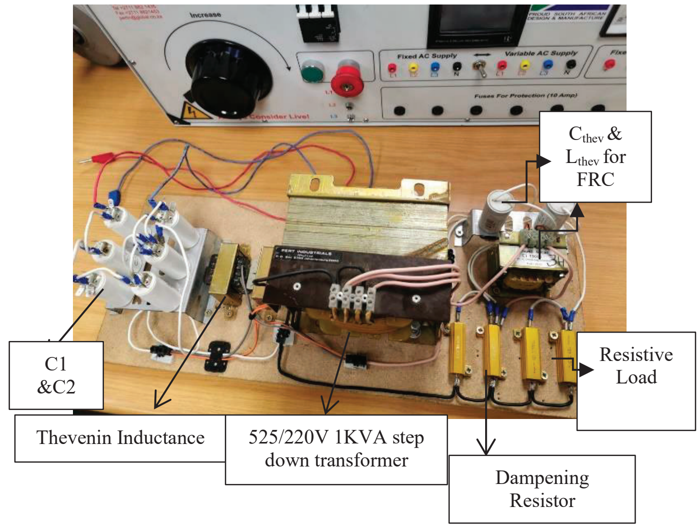

Fig 9 CCS Circuit practical setup

With 240 Vac supply voltage to the CCS, the following readings in table 1 were obtained.

Table 1: Voltages across measured on the CCS using a multi-meter

Across V_{C2}	32.27V
Across the Thevinin Inductance	20.39V
Primary side of the Transformer	12.97V

A. CCS with FRC and No-Load

A disturbance is initiated on the circuit, which lasts for 1 second. From Fig 10 and Fig 11, V_{C2} Voltage drops and stabilises quicker.

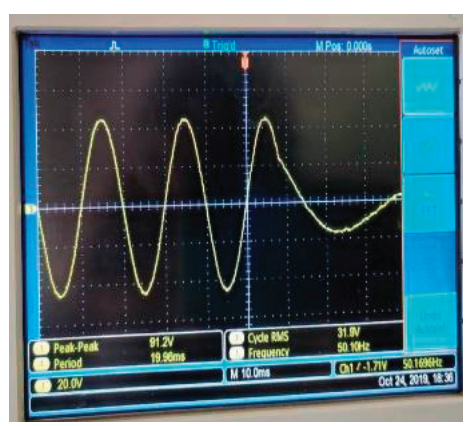

Fig 10 CCS with FRC and No-load: V_{C2}

Fig 11 CCS Voltage behaviour at Primary side of the transformer after the Inductance

B. CCS with No FRC and No Load (VC2)

A disturbance is initiated on the circuit, which lasts for 1 second. Figure 12 shows that V_{C2} oscillates when the CCS was switched back on depicting figure 8 of the simulation result.

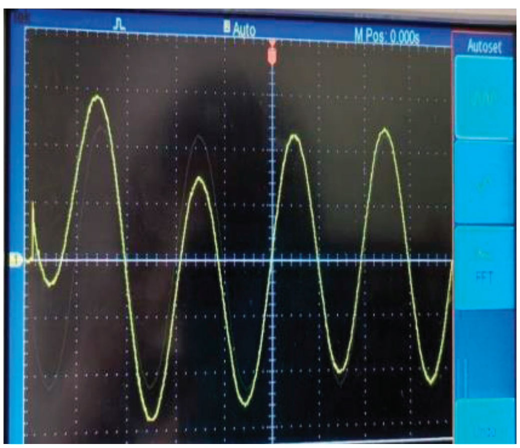

Fig 12 CCS with No FRC and No-load: V_{C2}

V. Conclusion

In this paper, switching transient analysis of capacitor-coupled substation (CCS) is presented. A CCS is modelled and simulated using MATLAB/Simulink, and an experimental prototype is developed for the transient study.

In both simulation and experiment, transient response of the CCS with and without Ferro-resonance circuit is investigated. Among many observations, it was generally observed through that the tapping voltage oscillates when the ferro-resonance circuit is not incorporated. Therefore, FRC circuit is critical in CCS technology, and care must be taken in its selection for transient stability of CCS.

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