Application of Three-Phase Vacuum Reclosers for Capacitor Bank Switching

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Abstract: This paper presents application considerations for three-phase vacuum reclosers when used for capacitor bank switching. To verify recloser performance, tests were conducted in two laboratories: CEPEL Brazil, and Thomas A. Edison Technical Center USA. The test setup consisted of two capacitor banks: one fixed and the another switched by the recloser. Test methods and results are presented for both. This paper also includes a root cause analysis of overvoltages recorded during testing, and gives guidelines for capacitor bank designs to prevent this type of overvoltage during bank switching.

Keywords: Capacitor Banks, Reclosers, Test Methods, Overvoltages, EMTP, ATP, Computer Modeling.

I. INTRODUCTION

Companhia Energetica de Minas Gerais (CEMIG) - Brazil is a state owned utility serving more than 5,000,000 customers. Its service territory covers 348,000 Sq. miles. Their system has approximately 5.9 GW of generating capacity, 13,160 miles of transmission lines at voltages up to 550 kV, and 180,130 miles of distribution lines. CEMIG requested Cooper Power Systems (CPS) to determine if three-phase reclosers could be used for their capacitor switching applications instead of single-phase switches used in the past (Figure 1), which have been presenting poor performance. In addition, reclosers can perform bus-bar short circuit protection, increasing substation selectivity.

A single-line diagram of typical capacitor installations is shown in Figure 2. Their capacitor banks are now assembled in racks, ungrounded double WYE-connected with ratings of 2400 kvar to 6000 kvar (steps of 1200 kvar). This design includes the following equipment: 15 kV, 630 A single-phase isolators; 15 kV, 560 A three-phase recloser; 15 kV, 75 μH, 300 A inrush reactors; 7960 V, 400 kvar power capacitors with internal fuses; 15 kV, 10x20/5 A, 10B200 current transformers; 12 kV, 10 kA, ZnO surge arresters; neutral current unbalance protection relays; local/remote automatic control.

The short circuit current at the bus is 10 kA symmetrical and 25 kApeak asymmetrical. Based on this data CPS performed an analysis to determine recloser operating characteristics for different capacitor switching conditions [1,2]. The Alternative Transient Program (ATP) was used for the simulations.

Model complexity was selected to obtain inrush current magnitudes, frequencies, duration of inrush currents, and steady state currents. Results indicated 15 kV, 560 A three-phase vacuum reclosers [3-5] can perform satisfactorily in such applications.

The next step was to perform laboratory tests. CEMIG suggested testing recloser operations in actual circuit arrangements with a total of 2,500 recloser close-open operations: 1,300 switching operations were performed in the CEPEL laboratory in Brazil, and 1,200 switching operations were performed in CPS's laboratory in the USA.

After the tests, reclosers were installed. The reclosers remain in service without problems after performing more than 12,000 capacitor switching operations.

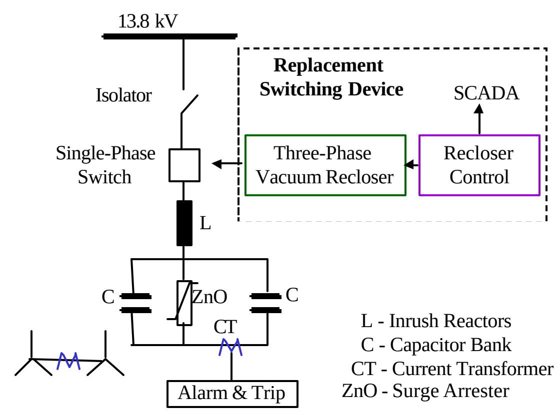


Figure 1. Single-Line Diagram of the Capacitor Bank Design

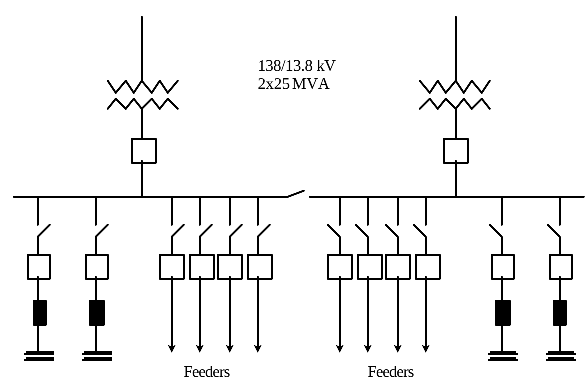


Figure 2. Single-Line Diagram of the Capacitor Bank Installations

II. TESTING IN CEPEL LABORATORY - BRAZIL

The test setup in Brazil consisted of a full size circuit configuration and equipment design to represent the most severe system conditions. Figure 3 shows the test setup, where the capacitor bank configuration (Wye ungrounded) was the same adopted by CEMIG in the past. This design included two capacitor banks: one fixed and one switched by the three-phase vacuum recloser. This configuration made it possible to test the influence of inrush currents from the fixed bank on recloser operation. The short circuit current at the capacitor bank bus was adjusted to 12 kA. Standard 5 kVA, 7960/240 V, single-phase distribution transformers were used in the capacitor neutrals for unbalance protection relays. The recloser control protection elements were set according to CEMIG's protection rules. The recloser source side voltages Vsa, Vsb, and Vsc were recorded on channels #1, #4, and #7. The recloser load side voltages Vla, Vlb, and Vlc were recorded on channels #2, #5, and #8. Currents Ia, Ib, and Ic were recorded on channels #3, #6, and #9. This order was applied in all figures.

Recloser close-open control was performed using the supervisory and remote operation features provided by the SCADA option of the recloser control [3]. Voltage and current waveforms were recorded using a digital recorder.

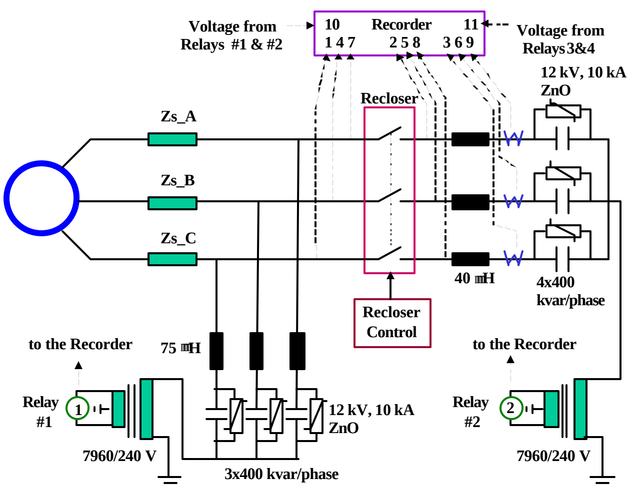


Figure 3. Test Setup for Testing in CEPEL Laboratory showing Neutral Transformers

Recloser contact resistance was measured at the beginning of the tests, used as a reference for measurements, and repeated after every hundred operations. Calibration tests were performed before actual tests to determine inrush current magnitudes and frequencies. Maximum peak values of inrush currents were between 5-6 kA with frequencies between 2.4-2.5 kHz, which was satisfactory.

During the first several tests no overvoltages were recorded. Figure 4 shows voltage and current waveforms representing one of these tests. It is evident that no excessive overvoltages existed across the recloser. The neutral voltage was calculated summing phase voltages. When the first current was interrupted, the neutral voltage started to develop. In this test it reached 15 kV_{peak}.

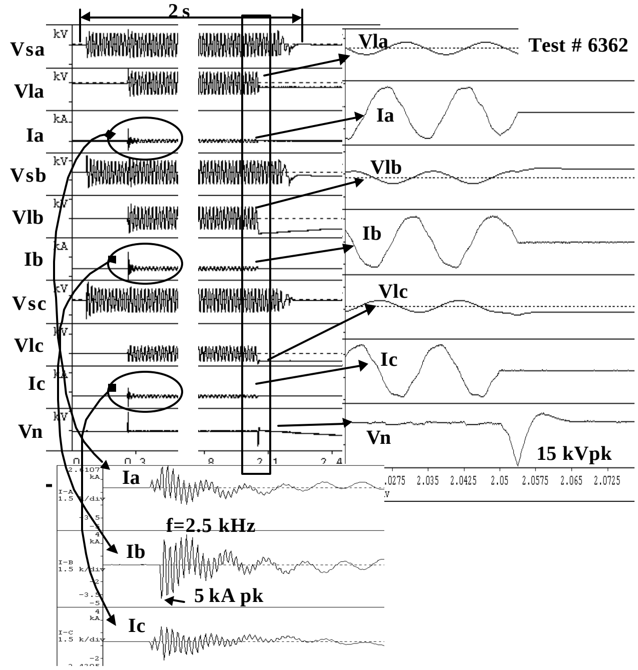


Figure 4. Voltage and Current Waveforms Recorded during the First 10 Capacitor Switching Tests; (shown: total event, inrush currents, and voltages and currents at the end of the event, no excessive overvoltages were recorded)

After 10 close-opening operations, the first higher overvoltages were recorded at the recloser load side as shown in Figure 5. Recloser load-side overvoltages were 57 kV_{peak} on phase A, 27 kV_{peak} on phase B, and 35 kV_{peak} on phase C. The peak value of the neutral voltage was calculated to be 40 kV. There was no evidence of a restrike on the current traces or on source-side voltages. Since these overvoltages were not excessively high, tests were continued. In the next several tests, no high overvoltages were recorded.

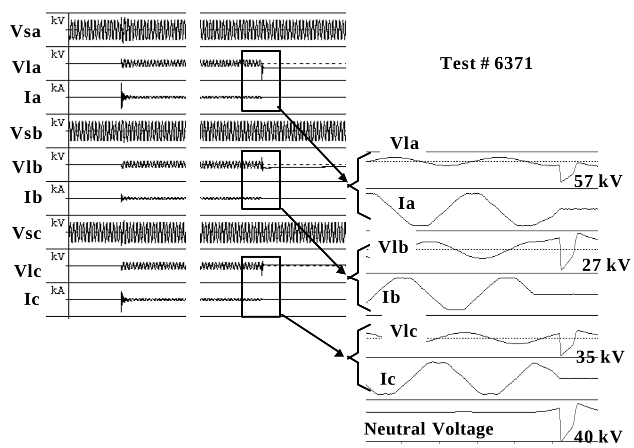


Figure 5. Voltage and Current Waveforms Recorded after First 10 Capacitor Switching Tests

During the 19th test shot, overvoltages were again recorded. Recloser load-side voltage in phase C (which interrupted last) reached 44 kV_{peak} as shown in Figure 6a. Overvoltages were again recorded in all other phases, 63 kV_{peak} in phase A and 31 kV_{peak} in phase B (Figure 6b).

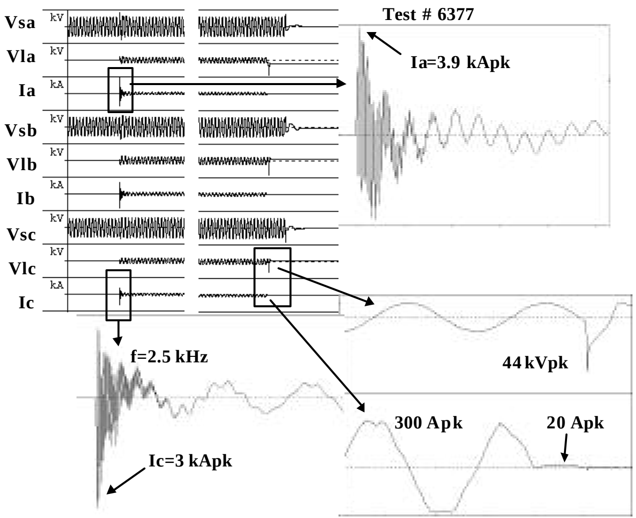


Figure 6a. Voltage and Current Waveforms Recorded during Capacitor Switching Tests

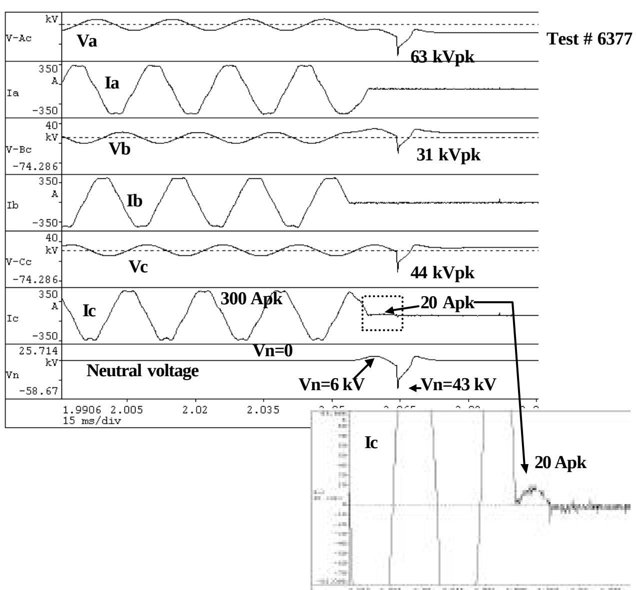


Figure 6b. Overvoltages Recorded during Capacitor Switching Tests with Neutral Transformers

The calculated peak value of the neutral voltage was 43 kV. Voltages across the recloser terminals were calculated from source-side and load-side voltage waveforms. Peak voltages were 74 kV on phase A, 23 kV on phase B, and 40 kV on phase C as presented in Figure 6c. Overvoltages on phase A reached an unacceptably high level, so it was necessary to find its cause and make corrections before tests could continue. This time an extended current loop in C phase was noticed (Figures 6a and 6b). It was suspected that distribution transformers for unbalanced voltage protection caused this type of overvoltage due to neutral shifting and flux buildup inside the core. The transformers had unnecessary high kVA rating for such an application with operating voltage of 7960 V. When analyzed Figure 4 again, it was concluded that even though no excessive overvoltages were recorded during capacitor current interruption in Test #6362, the neutral voltage shifted and reached 15 kV_{peak} with a duration long enough to generate flux quantity to saturate the core. Furthermore, the current was interrupted at this moment and remanent flux was trapped in the core.

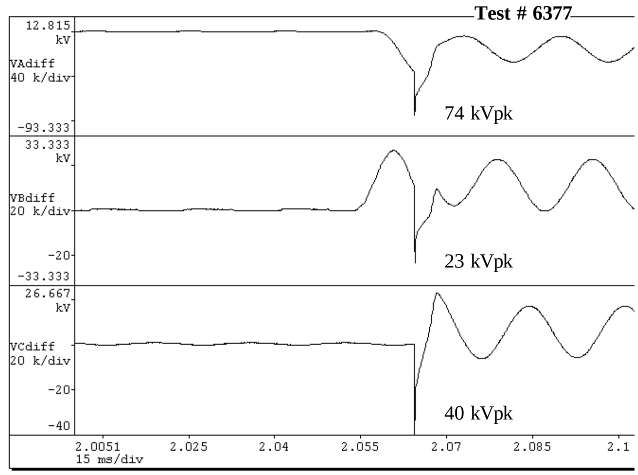


Figure 6c. Overvoltages across the Recloser Contacts Recorded during Capacitor Switching Tests with Neutral Transformers

Without a neutral transformer, there are only three currents (A, B, and C phases). The first current to cross zero will be the first current interrupted. The remaining two currents will be interrupted together. With a neutral transformer, there are four currents. The fourth current is the current flowing through the neutral transformer to ground. It can be neglected if the system is balanced or the neutral transformer does not saturate. But, when the transformer saturates due to flux build up in the core, the magnetizing branch impedance will decrease and the current will increase. Figure 6b shows the peak value of this current to be 20 A. During recloser opening, the first two currents to be interrupted are mainly capacitive. Figure 6b shows Ib current interrupting first. After the second current was interrupted (in this case it was current Ia), the circuit power factor changes due to the influence of the saturated neutral transformer. Current Ic does not pass through current zero with Ia and continues to flow for an extended current loop to reach the zero. The current is finally interrupted at the current zero of the extended loop, causing a high transient recovery voltage (TRV).

To explain why overvoltages were recorded in all three phases at the same time, voltages were plotted in phase with the currents as shown in Figure 7. When the first current was interrupted (in this case Ib current), significant neutral voltage was established. This same voltage appears on all phases superimposed on their phase voltages and coupled through the capacitors and inrush reactors since two recloser phases are open. Figure 7c shows load-side phase voltages shifted in the Y-axis to align overvoltages.

It is evident that all three phases have the same magnitude and direction. This voltage coupling is shown by the schematic diagram of Figure 8.

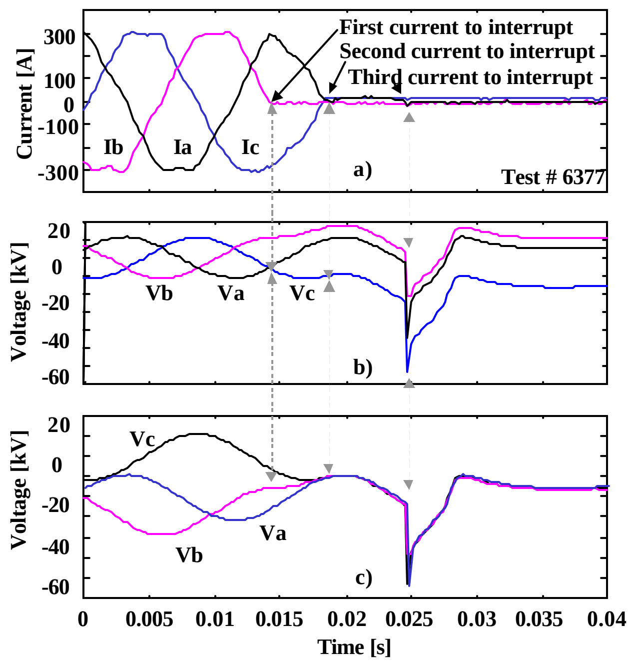


Figure 7. Voltage and Current Waveforms Recorded during Capacitor Switching Tests

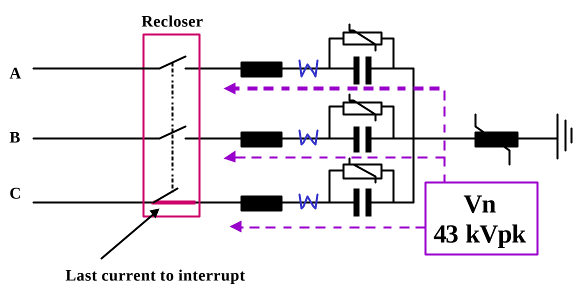


Figure 8. Neutral Overvoltage Distribution during Capacitor Switching Tests with Neutral Transformers

To confirm, computer simulations were performed using the ATP program. Neutral transformer saturation was simulated. Figure 9a shows total current, current through the neutral transformer, and currents with the extended current loop similar to the current loop recorded during tests. Simulated load-side voltages are presented in Figure 9b which shows waveforms very close to recorded values. Figure 9c presents simulated overvoltages across the recloser contacts during capacitor switching tests with simulated neutral transformer saturation. The TRV created across the switching device depends on the level of neutral transformer saturation.

Sensitivity analysis was also performed and indicated that if the neutral transformer leakage impedance is smaller than 100 times the capacitance impedance, overvoltages will likely to occur. In this paper, the neutral transformer leakage impedance was only 10 times higher than the capacitance impedance.

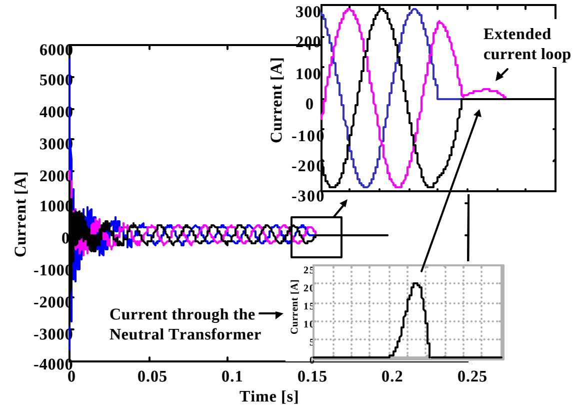


Figure 9a. Simulated Inrush Currents with the Neutral Transformer Saturation

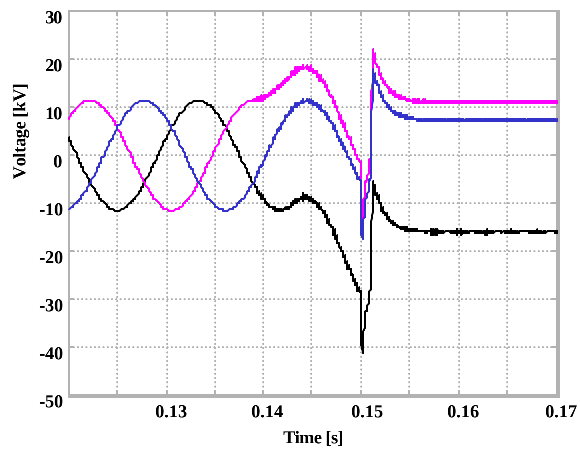


Figure 9b. Simulated Recloser Load-Side Overvoltages with the Neutral Transformer Saturation

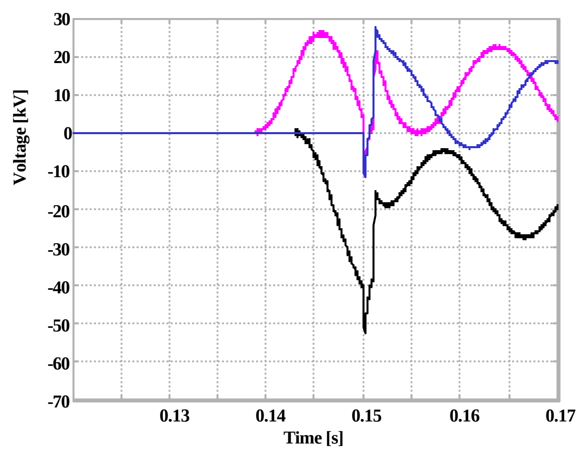


Figure 9c. Simulated Overvoltages across the Recloser Contacts during Capacitor Switching Tests with the Neutral Transformer Saturation

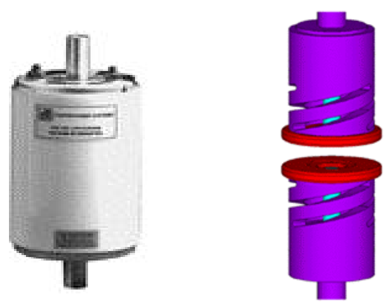
Without the neutral transformer, or if the neutral transformer does not saturate, the TRV becomes equal to the recovery voltage. The neutral transformers used for these testing based on their ratings could saturate. At what level saturation occurs is based on the probability that the flux in the core adds or subtracts from the flux trapped in the transformer core from previous switching operations. Capacitor neutrals shift during current interruptions, but shifts can also occur during closing periods if the contacts on all three phases do not close at the same time. The time difference between closing and opening of phases is more pronounced for single-phase switching configurations since switches are usually only electrically coupled and the three individual switching mechanisms may not have identical response time. To determine the time difference between switching of phases in the tested recloser, all recorded waveforms were analyzed. The largest time between any two phases was 0.5 ms, what is considered very good.

Based on these findings, distribution transformers were removed from the neutral and voltage dividers installed to monitor neutral voltages. There were no signs that overvoltages affected recloser performance, so tests were continued. During the remaining 1,280 switching operations, no overvoltages were recorded.

III. Testing in Cooper's laboratory – USA

A test circuit similar to the one in CEPEL's laboratory was setup at the Thomas A. Edison Technical Center in the USA. Test parameters were selected to meet ANSI C37-66 Standard for 400 A applications. This included a total of 1,200 tests: 400 tests at 100 A, 400 tests at 200 A, and 400 tests at 400 A. Voltages across and currents through the recloser were recorded. According to ANSI C37-66, a spark gap was installed on the recorder source side and set to operate at 2.5 p.u. voltage. During all 1,200 tests, no overvoltages were recorded.

At the end of testing, the voltage drop across the contacts was measured and compared to the voltage drop at the beginning of testing. There were no significant differences. Then, the vacuum bottles were opened and the contact surfaces inspected. Figure 10a shows a vacuum bottle (a) and the axial magnetic field vacuum interrupter contacts (b). Comparison between a new contact and one of three contacts at the end of testing is shown in Figure 10b. It is evident that contact erosion was very small and the contacts can successfully perform many more operations.



(a) **(b)**

Figure 10a. Vacuum Bottle (a), Vacuum Interrupter Contacts (b)

Figure 10b. A New Contact and Contact after 2,500 Capacitor Switching Operations

IV. Field Experience

Soon after tests were completed CEMIG installed 9 reclosers and then, next year, another 36 reclosers. The reclosers remain in service without problems after they performed over 12,000 capacitor switching operations. The capacitor banks are switched once a day in average.

The existing oil switching capacitor banks still experience many operational problems and failures so CEMIG is replacing 195 single-phase oil switches with three-phase reclosers in this year, and intends to continue with this policy for the remaining capacitor banks.

V. Application Considerations and Conclusions

Based on laboratory tests, computer simulations, and field experience of capacitor bank switching, the following application considerations and conclusions can be drawn:

When transformers are used for unbalanced voltage protection, neutral shifting and flux buildup inside the transformer core during capacitor opening can cause overvoltages. Neutral shifting may occur during capacitor closing as well as opening. Neutral shifting always occurs during opening, even if all three contacts seperate simultaneously. This is due to phase separation which forces one current to always cross zero first and be interrupted before the other two currents, causing unbalance and a neutral shift. If the contacts do not open simultaneously, neutral shifting will be more severe. Simultaneous contact operation and shorter pole spans are more likely for three-phase devices that are mechanically coupled than for single-phase devices that are electrically coupled.

In capacitor switching applications, three-phase reclosers with shorter pole spans between phases create lower overvoltages under these conditions. Three single-phase switches (electrically coupled) are more likely to cause damaging overvoltages.

Transformer parameters that must be considered when looking at such overvoltages are primary winding voltage and kva rating. Transformer primary voltage must be higher than the expected neutral shift to prevent flux buildup in the core. Sensitivity analysis indicated that low kva rating transformers will not cause such overvoltages.

Resistive or capacitive dividers will not cause this type of overvoltage because they are not subject to saturation and their kva ratings are low.

Field experience confirms three-phase, vacuum reclosers satisfactorily perform capacitor bank switching. However, previous and careful investigation as reported in this paper must be performed to take into in account the specific features of the others reclosers. It becomes truly important since there is no adequate standard covering this application.

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Biographies

Ljubomir A. Kojovic (SM '94) is the Chief Power Systems Engineer for Cooper Power Systems at the Thomas A. Edison Technical Center. He has a Ph.D. degree in power systems with specialties that include protective relaying, testing, digital modeling, and systems analysis. Dr. Kojovic is included on the roster of experts for United Nations Development Organization (UNIDO) and is a registered Professional Engineer in the State of Wisconsin. Dr. Kojovic has authored more than 100 technical papers.

Nelson S. Falcão is Sales and Marketing Manager for Cooper Power Systems in the Brazil office. He received is BSEE degree from the Polytechnic School of the University of São Paulo in 1980. He got a specialization in Reactive Power Compensation in Sweden in 1983, and worked in various SVC's and Series Capacitors projects for the Brazilian transmission system, when he authored several papers in this field. Since 1991, he's been working as Sales and Marketing Manager of electrical HV products, joining Cooper in 1995.

Juan R. Peraza received his BSEE from the Instituto Tecnológico de Cd. Madero - México in 1981. He worked for the Oil Company (PEMEX) in Mexico for 5 years as a Maintenance Engineer. He joined DMT Corporation in 1988 as a Design Engineer. In 1997 he joined Cooper Power System at Distribution Switchgear & Protective Relays Department, Kyle as a Distribution Protection Engineer.

Walter Aguiar Campos received his BSEE from the Polytechnic Institute of the Catholic University of Minas Gerais - Brazil in 1973. Formerly, he was the Chief Engineer of the Equipment and Materials Division in the Transmission Substations Design Department at CEMIG, where he worked for over 23 years. He is currently an independent consultant on high-voltage equipment.

Eduardo Nunes e Carvalho received his BSEE from the Phontific Catholic University of Minas Gerais in 1986. He joined CEMIG's Substation Engineering Department in 1987, where he is responsible for substation equipment supply. His expertise includes the technical analysis of bids, equipment specification and inspection, and consulting on the application of transformers, mobile stations, capacitors, voltage regulators, surge arresters and instrument transformer on 13.8 kV to 550 kV systems.

Luiz Henrique Silva Duarte received his BSEE and MEE from Phontific Catholic University of Minas Gerais in 1995 and 2000 respectively, specializing in Power Quality. His thesis deals with power capacitor operation in the presence of harmonic distortions. He joined CEMIG's Substation Construction Department in 1986. Since 1989, he has been working in the Substation Engineering Department. He is responsible for transmission and distribution system switchgear equipment specification and project management.

Magda de Rezende Nascimento received her BSEE from the Federal University of Juiz de Fora - Brazil in 1976. She joined CEMIG's Transmission System Planning Department in 1977 where she is responsible for studying and defining protection schemes, equipment specifications, substation layouts and performing overvoltage and overcurrent studies. She was a member of CIGRE - Brazil WG13-01 (Transient Recovery Voltage). She is a correspondent member of CIGRE - Paris WG13.08 (Management of Circuit Breakers) and coordinator of the same group in Brazil. She is a member of the Brazilian High-Voltage Circuit-Breaker Standard Study Commission.

Eleilson Santos Costa, joined the Center for Electrical Energy Research (CEPEL) as a Research Engineer in 1981. He is the manager of the Medium Power Laboratory and is responsible for the planning, coordination and execution of high power tests on electrical equipment. He is also chairman of the high-voltage enclosed switchgear and control gear standard commission (ABNT - NBR 6979 - Brazilian standard). His accomplishments include participating in technical commissions developing standards for circuit-breakers, transformers and high-voltage fuses, making presentations, preparing reports and publishing papers.

Henrique Burd, joined the Center for Electrical Energy Research (CEPEL) as a Research Engineer in 1979. He had his training in high power testing techniques in the laboratories of CESI, Italy. He was the Leader of the High

Power Unit of CEPEL from 1988 to 1997 and was responsible for coordinating high power tests on electrical equipment. During 1999 and 2000 he worked as Technical Advisor for GE Industrial Power Systems for Preliminary System and Final Performance Testing in the KEPCO high power laboratory in Seoul. His accomplishments include participating in technical commissions developing high power test methods for IEC and ABNT standards. Today he is the responsible of the certification office at CEPEL.