Mechanically Switched Capacitor with Damping Network (MSCDN) – Engineering Aspects of Application, Design and Protection

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Abstract – **The application of harmonic filters in transmission systems has experienced a fast increase in the last decade or more, as a result of the installation of new SVC and HVDC schemes. In addition, an innovative and cost-effective solution has been introduced some years ago and is already being used in several countries: the Mechanically Switched Capacitor with Damping Network (MSCDN). It consists in large shunt capacitor banks, arranged as a C-type harmonic filter, connected to high voltage systems to provide reactive power compensation and harmonic control, but with reduced losses in the resistor at fundamental frequency by means of a resonance between the reactor and auxiliary capacitor. This paper discusses design aspects of the MSCDN, providing relevant information and some recommendations regarding the specification and protection of the filter components. Regarding protection, innovative relaying schemes are presented to ensure reliability and sensitivity for internal faults on the components, in particular air-core reactors, in order to avoid major damage to them and allowing further analysis of the fault causes.**

Index Terms – **MSCDN, Reactive power compensation, C-type filters, transients, harmonics, capacitors, reactors, protection.**

I. INTRODUCTION

THE growth of the electricity market in several countries has demanded for new sources of reactive power to manage the power quality issues. In the last decade or more, lots of non-conventional power suppliers, including large wind farms, and high voltage direct current (HVDC) transmission systems have been planned and/or connected to the power grids. These new agents may introduce some harmonic currents at transmission voltage levels, which may excite system's harmonic resonances.

The large capacitor banks required at transmission levels are part of large substations where switching events, such as transformers energizations and bank switchings, are a frequent source of disturbance. Daily switching events and system disturbances may expose these banks to voltage and current waveforms with high rates of rise and long duration, which can reach tens to hundreds of milliseconds and may be classified as dynamic surges. There would be no problem regarding thermal issues, but it will submit the equipment to high dielectric and mechanical stresses, which can cause a reduction in the operational life of the equipment with serious risk of failure, if not properly considered in the design stage. Thus, harmonics and transient analysis are a major concern in the design of capacitor banks for power compensation in high voltage systems. For many applications the expected bank switching operations are around 4 times per day, and mechanically switched capacitor (MSC) banks are often used for this purpose. The topology of these MSC can be that of a single capacitor bank with or without damping reactor, or a single tuned harmonic filter

Regarding the harmonic performance it is strictly required that the new MSC banks do not produce any significant magnification of the pre-existing harmonic distortion in order to not worsen the current situation.

Considering the above mentioned, the C-type harmonic filters, also called Mechanically Switched Capacitor with Damping Network (MSCDN), is a cost-effective solution. It may provide large MVAr amounts with no harmonic magnification and almost no losses at fundamental frequency.

Several MSCDN have been installed in the high voltage grid of different countries in the last years. Among them we may cite: 225 Mvar at 400 kV and 150 Mvar at 275 kV in the UK; 150 Mvar at 380 kV and 220 kV in the Netherlands; 250 Mvar and 300 Mvar at 380 kV in Germany; 100 Mvar at 400 kV and 220 kV in Spain; 150 Mvar at 275 kV in South Africa; 60 Mvar at 275 kV in Malaysia.

II. THE C-TYPE HARMONIC FILTER

A C-type harmonic filter is normally tuned to 3rd harmonic order and its main components are: main capacitor, tuning capacitor, tuning reactor and damping resistors [1][2][3]. A detailed formulation for calculation of the component parameters is presented in [1]. The basic topology of C-type filters is shown in the Fig. 1.

The operation of the C-type filter is quite different than a simple tuned filter bank. At fundamental frequency, the capacitive reactance of the tuning capacitor and the inductive reactance of the tuning reactor cancel each other and the damping resistor is completely bypassed, preventing steady state losses. Under these operating conditions, only the main capacitor is effectively in service, providing the reactive power required for system compensation and voltage support. For the rest of the frequency spectrum the c-type filter behaves like a high pass filter heavily damped. This is an interesting feature, since its flat frequency response curve prevents any possible resonance with the network harmonic impedance.

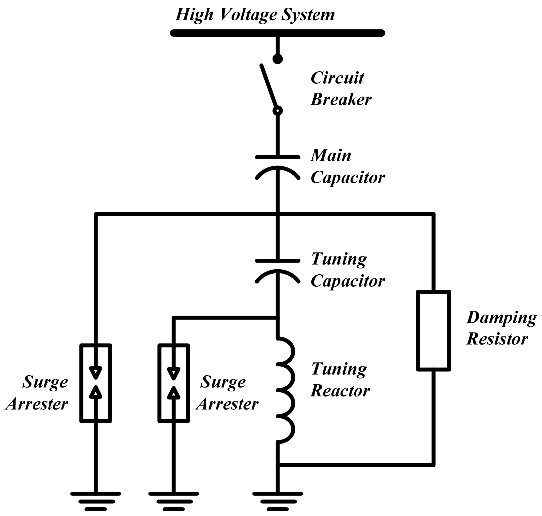

Fig. 1 – Single-line diagram of C-type filter

The same does not occur for single capacitor banks, which may create serious resonance problems as they may combine with the system impedance, and for single tuned harmonic filters, which always create a resonance condition at a frequency below its tuning frequency.

Fig. 2 shows typical frequency responses for a single capacitor bank, a single tuned filter and a C-type harmonic filter.

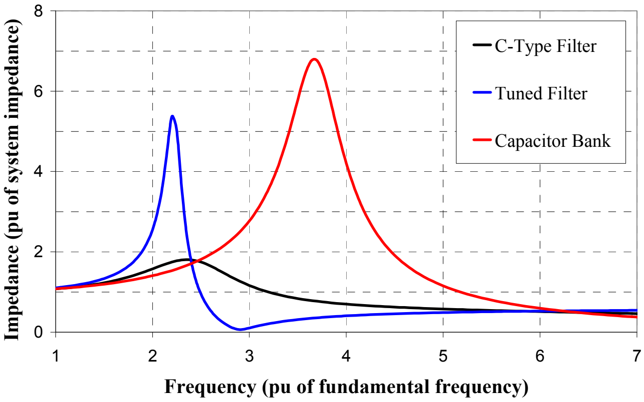

Fig. 2 – Frequency response of capacitor banks and harmonic filters

In practical harmonic analyses the harmonic impedance is calculated with software programs based on a specific network configuration. The transmission system can be operated under a variety of contingencies and generation dispatches that lead to different short circuit levels and impedance characteristics. A number of these cases generate then a harmonic impedance area, which determines the most severe rating or performance specifications. The results of these programs represent the harmonic impedance in terms of an R-X polar plot, for each harmonic order, as shown in the Fig. 3. This impedance boundary is designated a resonance circle, with Rmax corresponding to the first parallel resonant point of the network [4][5].

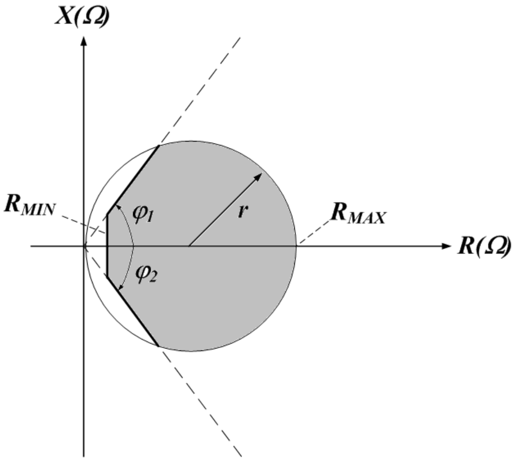

Fig. 3 – Harmonic impedance loci

The installation of large capacitor banks at transmission voltage levels, introduces a low order resonant frequency in the system, resulting from the parallel combination with the system's impedance. When a MSCDN design is used, the high damping over the frequency range of interest reduces the maximum radius in the impedance loci in Fig. 3 and drops down the resonance peaks for the bus impedance, with a reduction in the resulting harmonic voltages per unit of injected harmonic current.

III. ENGINEERING STUDIES

Engineering studies shall be always performed to properly define the ratings of the MSCDN components. In addition to the steady state load flow, these studies mainly comprise harmonic and transient analysis for definition of current and voltage stresses on the capacitors, reactors and resistors. The standard IEEE Std. 1531 [6] is a useful guide for evaluation of harmonic filters and it gives detailed information about the procedures for performing these studies.

It is always recommended to include these studies, or at least their main results, in the performance specification of the filter components. This technical information should include continuous, temporary and transient voltages and currents on the capacitors, reactors and resistors. Tables showing different harmonic loadings and waveshapes of worst-case transients should also be provided.

A. Harmonic analysis

The harmonic analysis of a MSCDN should consider at least, but not limited to, the following operating conditions:

- System normal operation;
- Background harmonics, existing or coming from other harmonic sources in the vicinity;
- Temporary harmonic due to the change of load profile;
- Harmonic currents coming from system transients and disturbances, such as transformer or line energization, system faults, reclosing, etc;
- Predicted future harmonics.

The MSCDN components shall be properly designed to withstand the thermal and dielectric effects of steady-state, temporary and transient harmonic loading created by the different conditions mentioned before.

Particularly, the system events that cause transformer or reactor saturation (e.g., transformer or reactor energization, clearing of nearby faults, etc.) may result in severe temporary duties and increase the harmonic currents through the filter.

B. Transient Studies

A MSCDN is typically intended to operate for 12 hours on average each day and switched on and switched off each day, i.e. an anticipated duty of more than 700 switching operations per annum.

Daily switching events and system disturbances may expose the filter components to non-standard short-time and transient voltages and currents with high rates of rise and long duration, reaching tens to hundreds of milliseconds, which may be classified as transient and dynamic surges. These surges will submit the equipment to high dielectric and mechanical stresses and may reduce the service life of the equipment with serious risk of failure, if not properly considered in the design.

Although point-on-wave synchronized circuit breakers are generally used for this application, it may not be considered in the transient analysis to have more conservative results.

As primary overvoltage protection, surge arresters are installed across resistors and, in some cases, across reactors, to limit the transient and dynamic overvoltages on these components, mainly when POW breaker is not operating. These surge arresters may be subjected to several current injections per day, in a frequency of occurrence much higher than typical operation regime, considered to be imposed to common surge arresters. Thus, the manufacturer shall be informed and confirm the ability of the surge arresters to handle these daily stresses without presenting any excessive heating, fast ageing or change of their electrical performance.

The transient voltage and current stresses on the MSCDN components, and the surge arrester protective level and energy absorption may be determined and evaluated by the following conditions:

- Energization of one or more filter banks in parallel, at minimum and maximum system short-circuit levels, and for different closing time within the point-of-wave range.
- Switching surges, simulated by applying surge voltages (250/2500 μs) to the filter banks.
- Lightning impulse surges, simulated by applying standard (1.2/50 μs) and chopped voltages to the filter banks, equivalent to shielding failure and back flashovers.
- Occurrence of system faults nearby to the filter banks (single phase and/or three phase fault to earth).

A practice often adopted by some utilities is to select the Lightning Impulse Withstand Level (LIWL) of the MSCDN capacitors, reactors and resistors as being at least 25% higher than the respective maximum peak transient voltage, which correspond to the highest possible arrester residual voltage. The Switching Impulse Withstand Levels (SIWL) for the component resistors and reactors are estimated as being around 80% of their Lightning Impulse Withstand Levels (LIWL).

IV. DESIGN ASPECTS OF MSCDN COMPONENTS

A. Capacitors

The main concern in the design of capacitor banks is the transient and dynamic overvoltages across the capacitor units, since it may cause internal insulation failures and external flashovers. The capacitor units are covered by standards IEEE Std. 18 [7] or IEC 60871-1 [8].

According to IEEE Std. 18, capacitor units shall be designed for continuous operation without exceed none of the following limitations: 110% of rated rms voltage; 120% of rated peak voltage, i.e. peak voltage not exceeding $1.2 \cdot \sqrt{2}$ times the rated rms voltage, including harmonics, but excluding transients; 135% of rated rms current based on rated kvar and rated voltage and 135% of rated kvar.

IEEE Std. 1531 [6] recommends that the rated rms voltage U_C of a capacitor unit shall be selected as the greatest of these three values described below:

- For steady-state operation, the rated rms voltage shall be the arithmetic sum of the power frequency and harmonic voltages, as given by the equation (1).

$$U_C \geq U_{C_1} + \sum_{h=2}^{\infty} X_{C_h} \cdot I_h \qquad (1)$$

- For transient events, such as bank switching and breaker restrike, the rated rms voltage shall be calculated from the equation (2).

$$U_C \geq \frac{U_{TR}}{K \cdot \sqrt{2}} \qquad (2)$$

Where U_{TR} is the maximum peak transient voltage and K depends on the number or yearly transients given in the Fig. 4.

- For dynamic events, such as transformer energization and fault clearing, the rated rms voltage shall be derived from equation (3).

$$U_C \geq \frac{U_D}{\sqrt{2}} \tag{3}$$

Where U_D is the maximum peak dynamic voltage and the number of dynamic events per year shall not be more than 300.

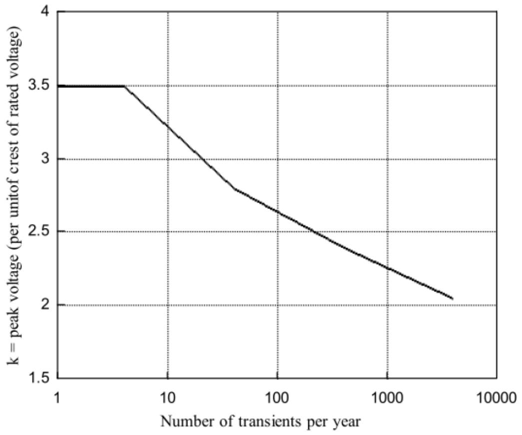

Fig. 4 – Transient overvoltage capability of capacitor units, as per IEEE Std. 1531 [6]

In general, the power frequency overvoltage capability is expressed in terms of the duration and number of times that overvoltages occur during service life of the capacitor, as shown in the Fig. 5.

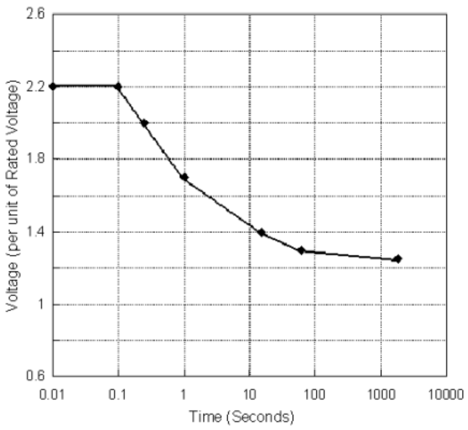

Fig. 5 – Power frequency overvoltage capability of capacitor units, as per IEEE Std. 1531 [6]

B. Reactors

The design of tuning reactors is evaluated in terms of thermal, dielectric and mechanical criteria. This equipment is covered by the standards IEC 60076-6 [9] and IEEE C57.16 [10]. The standards usually provide general design guidelines, testing procedures and basic requirements for general filter applications. However, special care must be taken when elaborating the specification for MSCDN reactors, mainly concerning the harmonic current spectra, the transient and dynamic overcurrents and overvoltages, with their respective amplitudes, durations and frequencies of occurrence.

The harmonic currents through reactors cause both thermal and dielectric stresses on the winding. It must be noted that the impedance of the reactor increases with higher frequencies, thus the knowledge of the complete harmonic spectrum with each current value and frequency is important to allow the manufacturer to evaluate properly the voltage drop along the coil winding.

The thermal effect of each harmonic current on the reactor winding and other components depends not only on the current and frequency figures. The skin-effect and induced losses will be influenced also by the rated power, shape of the coil, geometry and electrical properties of the winding or component. It means that each manufacturer shall consider the thermal effect of the harmonic spectrum on its project. The equivalent fundamental current determined by the root-sum - square of the harmonic currents which is commonly specified for filter reactors has no physical sense, either by dielectric or thermal effect analysis.

Therefore, the specification of the complete spectrum with maximum current values at each frequency is mandatory to allow the manufacturer to design the appropriate reactor, in order to withstand these thermal and dielectric stresses. If some harmonic currents and frequencies are not expected to occur simultaneously, more than one harmonic spectrum may be specified, in order to achieve an economic design that fully meets all harmonic requirements.

For analysis, the equivalent fundamental current I_{EQU} shall be the calculated value of current at power frequency which gives the same winding losses as those arising from the power frequency current and harmonic spectrum, as given by the equation (4).

$$R_{AC_1} \cdot I_{EQU}^2 = R_{AC_1} \cdot I_1^2 + \sum_{h=2}^{n} R_{AC_h} \cdot I_h^2 \tag{4}$$

Procedures to calculate the equivalent fundamental current from measured figures must take into account that a significant part of the AC resistance measured on a filter reactor at a given frequency is derived from induced losses on components other than the winding itself, such as the cross-arms, mounting pads, brackets and corona rings, among others. In order to calculate I_{EQU} properly, the manufacturer shall provide the design data to allow determining the share of AC losses on the winding of the reactor.

Generally, reactors are insulated for reduced BIL between terminals and terminal-to-ground, since they are installed in the neutral side of the main capacitor bank. Worst-case transient and dynamic overvoltage across the reactors shall be also informed to the manufacturer for evaluation of internal insulation stresses. All transient and dynamic overvoltage surges must be specified not only by magnitude, but also by duration and frequency of occurrence, for the proper design of the reactor to prevent reduction of its operating life.

The reactors are not exposed to system fault currents due to their position in the capacitor bank arrangement. However, reactors shall be designed to withstand mechanical effects of daily transient currents of the routine switching events, i.e., with high repetition rates. Dynamic overcurrents shall be specified by magnitude, duration and frequency of occurrence.

Surge arresters are often installed across the winding to provide overvoltage protection against lightning and switching surges, which may have higher magnitudes, rise rates and duration than those found in typical harmonic filters. Also, the frequency of occurrence of surge arrester operation must be considered. The transient studies shall be performed considering the high frequency model of the reactors, as shown in the Fig. 6, where series capacitances C_S and capacitances to ground C_G should be informed by the manufacturer.

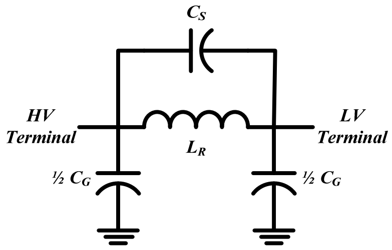

Fig. 6 – Reactor model for transient studies

At fundamental frequency, since the damping resistor is bypassed, the losses on the reactors shall be as low as possible and therefore a high Q-factor is desirable. On the other hand, in all other frequencies equal or above the tuning frequency, the Q-factor is not relevant since the resistor is not bypassed anymore and therefore, natural Q may be specified.

Other technical issues concerning the reactors are: the magnetic field constraints, which shall be evaluated in order to avoid induction in metallic parts in surrounding areas and the total sound power emitted by the coils due to mechanical vibration caused by the fundamental and harmonic currents. Normally, currents specified to thermal evaluation of reactors shall take into account the complete harmonic current spectrum coming from normal operation, temporary overloads and transient events, such as transformer energization.

C. Resistors

As per tuning reactors, the harmonic current spectrum through the damping resistors shall be defined for continuous (normal) and temporary operation. This spectrum determines the heating and losses on the resistor elements, as well as the vibration and noise generated. To provide some margin to unexpected current, design current is calculated by arithmetic sum of the individual contributions.

Surge arresters are always used in parallel to the resistors to limit the transient and dynamic overvoltages and the insulation level (BIL) has also a reduced value, considering they are installed in the neutral side of the main capacitor bank.

V. PROTECTION ISSUES

A. Overview of MSCDN Protection

Protection is a key point in the design of any kind of capacitor banks, including the MSCDN. The main targets of the filter bank protection are: overvoltages, overcurrents and unbalances.

Primary overvoltage protection is assured by the main bus protection and also by the surge arresters installed across the reactors and resistors. As any high voltage capacitor bank, the MSCDN requires a broad range of protection relays to monitor voltage and current on the capacitors, reactors and resistors. Protection solutions may use several relaying schemes depending on the designer experience. This is detail discussed in [11].

Fig. 7 shows a typical relaying scheme for a MSCDN [12], which will be discussed in the following items.

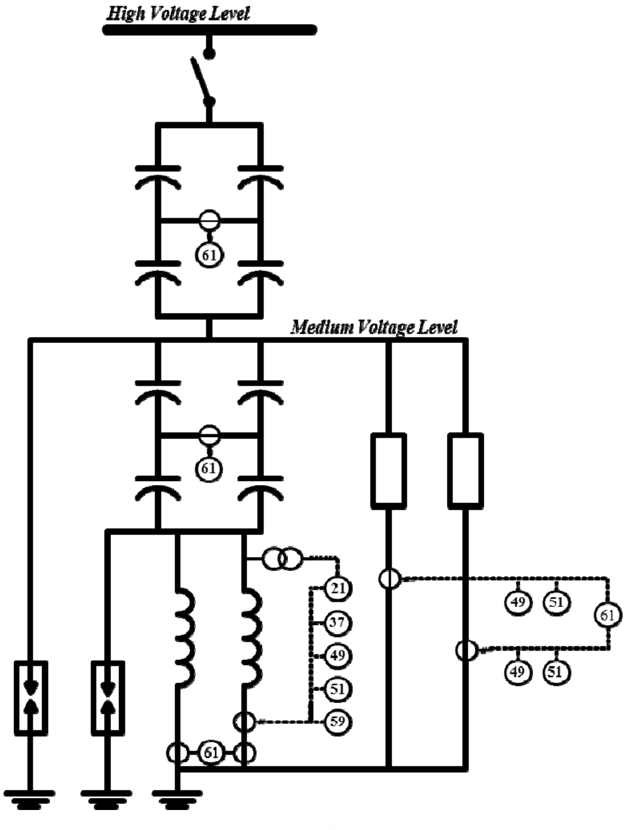

Fig. 7 – C-Type Harmonic Filter – Protection Scheme

B. Protection of Capacitor Banks

Protection for the main capacitor is provided by a current unbalance relay (61) that monitors the unbalance current in the H-bridge connection [11][12]. Two levels of protection are often applied: alarm and trip. Alarm setting is chosen to detect a single series section failure, with an appropriated margin of 80% of the calculated value. Trip setting is chosen to detect multiple series section failures.

The bank should be taken off line before the remaining capacitor sections are subjected to a voltage greater than 110% of their rating. Capacitor units of main section can be internal fuse or fuseless type and their strings are rated for a voltage higher than nominal value.

A capacitor unit failure is detected in the tuning section in the same manner as that of the main capacitor section. A separate overcurrent relay (61) is used, one per phase. The tuning section capacitors can be also fuseless or internal fuse. Since the tuning section is not just a single capacitor bank, the calculation of the unbalance current is somewhat different than for the main capacitor section. Also, this protection is only sensitive to problems in the capacitor bank. It will not detect a reactor shorted turn. This is accomplished by another protection scheme, as shown below.

C. Protection of Reactor

The dry type air core reactors used in harmonic filters are single phase units assembled in a three-phase bank, with relatively large distances between units and to earth. In these arrangements faults between phases and between phase and earth are rare. Hence, our main concern regarding reactors protection is the possible winding insulation failures. These failures can begin as tracking due to surface contamination, insulation deterioration or as turn-to-turn faults. Once an arc is initiated, these failures, if not detected promptly, can flashover the entire winding due to the strong interaction of the arc with the magnetic field of the reactor, leading to a phase to neutral fault, destroying the winding [6].

The current and voltage changes encountered during a turn-to-turn fault can be of the same order of magnitude as variations expected in normal service, making it a formidable challenge to the protection engineer. To overcome that a combination of protection functionalities is necessary in order to achieve proper reactor protection. It includes an undercurrent or under power relay (37), a distance relay (21), a machine, or reactor thermal relay (49), an overvoltage relay (59), an A.C. time over current relay (51) and current unbalance relay (61). When the reactor begins to fail due to shorted turns, the tuning between the reactor and tuning capacitor is lost and the total impedance of the filter bank begins to increase. This increase in bank impedance will cause a decrease in the amount of current flowing through the reactor. Thus, an undercurrent relay (37) can be used to monitor the reactor current and detect this failure of the tuning reactor.

Changes in reactor impedance can be used to enhance the protection against shorted turns. A distance relay (21) monitoring the fundamental frequency voltage and current across the reactor can be used to determine the actual reactor impedance on a per-phase basis. The sensitivity of this protection is able to detect a single shorted series section and issue an alarm with identification of phase-involvement. If the number of shorted series sections is large enough to cause an impedance range shift beyond the alarm region, then a trip command is issued.

Thermal image relays are used to protect the reactor from a possible overload condition caused by excessive exposure to harmonic current. The reactor manufacturer can provide the analytical expression, together with its defining parameters (time constants and others) in order to define the thermal protection algorithm applied to estimate the temperature of the winding hot-spot.

The harmonic overvoltage relay monitors the instantaneous harmonic reactor voltages. The harmonic voltage are summed arithmetically and compared to a set value which provides sufficient tum-to-turn overvoltage protection.

Finally, fundamental frequency overload is detected by a A.C. time over current relay (51).

D. Protection of Resistor

Since at fundamental frequency the tuning branch is close to a short circuit, under normal operation there will be only harmonic current in the two resistors [12]. Thus, a simple rms (harmonics included) A.C. time over current relay (51), one per-resistor and per-phase basis, can be used. However, due to the possibility of short-term repeated rms current overloads, it is also necessary to use a thermal image relay (49), employing thermal time constants of the resistors and permissible temperature rise allowed, in a form similar to that used for the reactors.

The number of resistors used is a design criterion. If more than one is used then a current unbalance protection (61) can be used to detect either an opened or shorted resistor, a situation when only very small harmonic current flows through the resistor.

Current unbalance protection relay (61) is applied to protect the two separate resistors, since currents in the two resistors are expected to be identical as identically rated resistors and CT are used.

E. Recommendation on Relaying Settings

The relaying settings shall be made with basis on the capabilities of the MSCDN components, given in the respective standards.

Capacitor units shall be designed for continuous operation without exceed none of the following limitations [7]: 110% of rated rms voltage; 120% of rated peak voltage (i.e. peak voltage not exceeding times the rated rms voltage, including harmonics, but excluding transients; 135% of rated rms current based on rated kvar and rated voltage and 135% of rated kvar. Therefore, two levels of overcurrent protection that monitor the unbalance current in the H-bridge are often applied: alarm and trip. Alarm setting is chosen to detect a single series section failure, with an appropriated margin of 80% of the calculated value. Trip setting is chosen to detect a second or multiple series section failures.

Unlike the capacitor units, reactors do not have a well-definite strength in terms of their ratings. It depends on several design aspects such as design temperature, temperature class of insulation, insulation and conductor materials, conductive cross-section of winding, coil dimensions, etc. All of these variables together will determine the voltage and current capability for each reactor. Manufacturer can provide plots, tables and analytical expressions to give the reactor withstand levels for different period of times.

An important issue is the sensitivity of the protection settings, particularly for the tuning section. In order to compensate for the inherent unbalance that may exist under health bank condition, a nulling logic is incorporated into the relay. This logic uses the error signal measured during bank commissioning to compensate the real-time protective algorithms [12].

VI. ALTERNATIVE REACTOR DESIGN

The reactors of the tuning branch can be design in such a way to allow the insertion of current transformers to be connected between two half-coils connected in parallel allowing a faster detection of the internal faults. This kind of arrangement is called reactors in split-phase.

A current transformer is connected between the coils, feeding an unbalance current relay (61). The CT must have two primary windings to be connected in opositive polarity, allowing the current to be close to zero. Fig 8 shows the connection scheme.

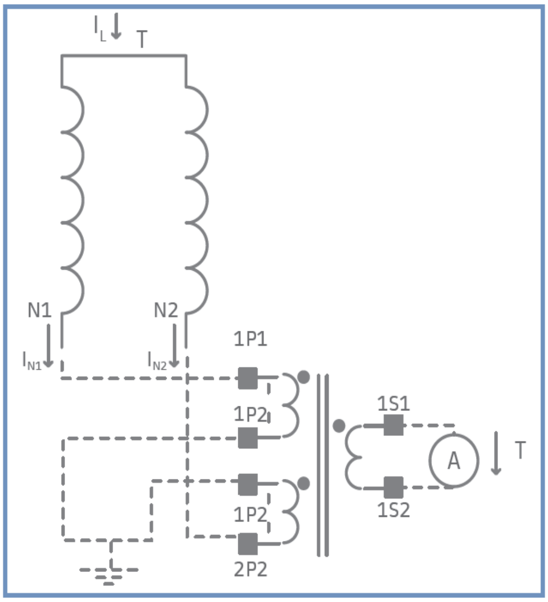

Fig. 8 – Connection scheme – Reactors in split phase

Shorted turns in this case will create an increase on the current being then sensitively detected by the unbalance relay that shall be preset considering the inherent unbalance current, informed by the manufacturer based on as built design, also considering the steady state conditions of the MSCDN.

Fig. 9 shows the arrangement of a reactor in split phase connection.

Fig. 9 – Arrangement – Reactors in split phase

VII. CONCLUSIONS

The MSCDN is an economical solution for reactive power compensation and harmonic filtering at transmission voltage level. These large sources of compensation are very relevant for system operation. If they are switched off due to some failure, the system will have to operate under some kind of constraint. This paper has shown many challenging engineering aspects that a design Engineer must consider in order to achieve an acceptable level of reliability when designing a MSCDN system. Careful specification of filter components, considering harmonic and transient voltage and current stresses together with appropriate protection schemes, as discussed in the text, will prevent unanticipated failures, thus assuring a reliable and cost effective solution.

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IX. BIOGRAPHIES

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Since 2010, he was with Alstom Grid factory of air core reactors, capacitors, capacitor banks and line traps, in Itajubá, Brazil, first as a trainee in the ALSTOM's trainee special program, with experience in all the main areas of the factory of air insulated switchgear and also in turkey substation projects. Since 2011, he is export sales engineer having started his master degree course in electrical engineering with emphasis in power quality.