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Switching Transient Mitigation By Controlled Switching: A Literature Survey

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Energy is one of the major inputs for the economic development of any country. This is the reason electrical power system network is expanding day by day to serve the increasing energy demand of the nation. There are many types of equipments in power system.A circuit breaker is protective switching equipment and hence, it plays a very important role in the power system. To maintain the adequate reactive power for voltage control in EHV & UHV system, frequent switching of capacitors and reactors is required through circuit breaker.These are the few applications where switching transients can occur frequently.Apart from this unloaded transformer and transmission line energization also leads to inrush current and over voltages in the system. This condition results into electrical and mechanical stresses and sometimes may lead to equipment failure. Controlled switching has become an economical and technically viable solution to reduce switching transients. This paper presents a literature survey based on switching transients and controlled switching aspects.IEEE transactions,conferences, CIGRE reports andvarious catalogues of the controllers are referred for the literature survey. This survey ishelpful for the researchers working in the area of controlled switching, circuit breaker manufacturers,controller manufactures and power utilities.

Keywords: *preinsertion resisor , re-ignition, restrike,controlled switching, RDDS, mechanical scatter, making window, making instant, adaptive control*

1.0 INTRODUCTION

Anyelectrical circuit has got resistance, inductance and capacitance parameters and the combination of the same. Under steady state condition the energy stored in inductance and capacitance is being transferred cyclically between Land C of the circuit [1]. The energy transfer is represented in equation (1.1)

$$\frac{1}{2}LI^2 = \frac{1}{2}CV^2 \qquad ....(1.1)$$

$$I = \frac{V}{\sqrt{L/C}} \qquad ....(1.2)$$

Switching surges occur on power systems as a result of instantaneous changes in the electricalconfiguration of the system, refer equation (1.2) Such changes are mainly associated with switching operations andfault events. These over voltages generally have crest magnitudes which range from about 1 per unit to 3 pu for phase-to-ground surges and from about 2 to 4 pu for phase-to-phase surges with higher values some times encountered as a result of asystem resonant condition. Wave shapes vary considerably with rise times ranging from 50 µs tothousands of µs and times to half-value in the range of hundreds of ms to thousands of ms[2]. For insulation testing purposes, a waveshape having a time to crest of 250 µs with a time to half-value of 2500

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μs is often used.The circuit components gets overstressed due to switching transients and it can lead to protection mal operation, equipment failure, plant shut down, etc.

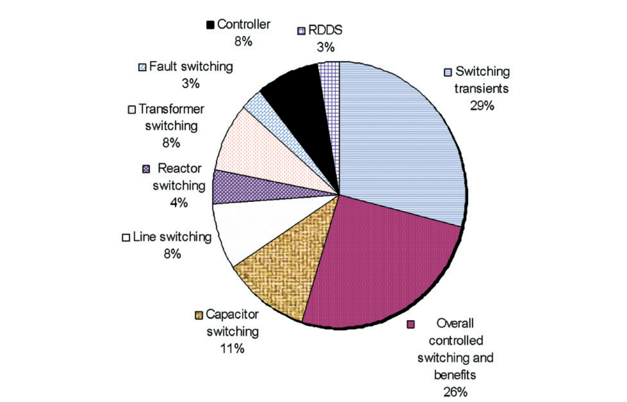

FIG. 1 AREAS OF LITERATURE SURVEY

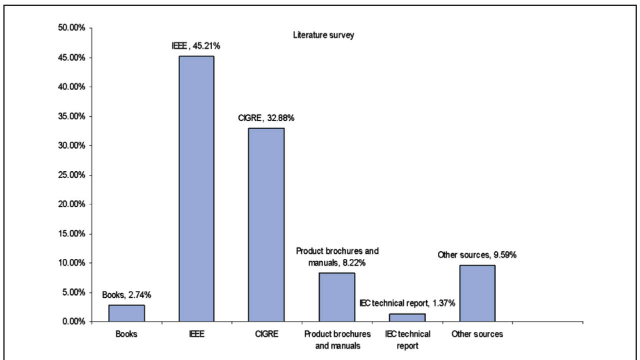

FIG. 2 LITERATURE SOURCES

Controlled switching of circuit breaker is a new method which is becoming popular day by day for the electrical transient mitigation in case of HV, EHV and UHV transmission system. Controlled switching is nothing but switching the load at the optimum point on voltage or current wave so that the switching surges will be minimum possible.

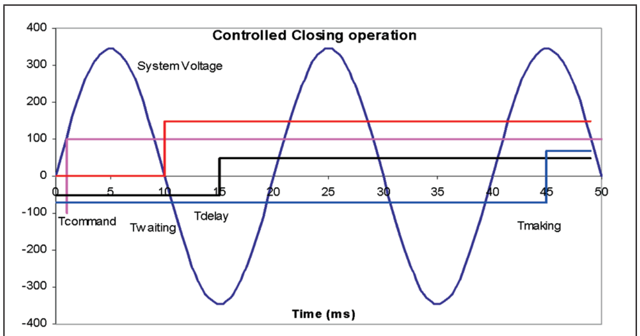

FIG. 3 CONTROLLED CLOSING EXAMPLE

The example sequence shown in Figure3 relates to controlled closing of an inductive load, where the optimum closing instant is at a voltage peak. The similar philosophy works in controlled opening only difference is current is taken as reference signal preferably and the target instant is such that to ensure maximum arcing time before current zero.

Till recent time many researchers have done work to address the controlled switching challenges&solutions. The review is divided into nine major areas related to switching transients and it'smitigation by controlled switching as shown in Figure 1. The referred publication for literature survey is mainly from IEEE transactions, conferences, CIGRE reports, books, instructionmanualsand cataloguesfrom controller manufacturers, IEC standards & other conferences as represented in Figure 2.

2.0 SWITCHING TRANSIENTS

In the era of early 40's researchers have done work on the resistance switching for the mitigation of switching transients [3-4]. The damping of recovery voltage doesn't depend on the absolute value of the resistance but the value of resistance relative to the inductance and capacitance of the system [3]. There are different switching conditions which give rise to voltage or current transients like capacitor energization, unloaded line switching, inductive load switching, transformer switching,fault etc.

Capacitor is a very important component in the electrical power system. Reactive power compensation and power factor improvement are the two main requirements of the power system which makes capacitor existence mandatory in the system. Capacitor closing gives rise to high inrush current and overvoltages if switched randomly and without using resistor or reactor in the circuit as shown in Figure 4, Capacitor opening becomes the very critical as 2 p.u voltage comes across the breaker contacts which may lead to a restrike condition and voltage escalation.

The impact of switching transients in case of capacitor bank switching i.e. energization and de-energization is very severe if mitigation is not provided. Frequent energization transient of back to back capacitor banks can cause the failure of capacitor bank itself and circuit breaker [5-8].

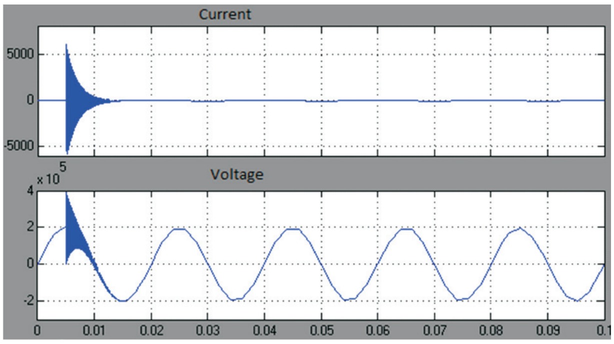

FIG. 4 CAPACITOR CLOSING CURRENT (WHEN SWITCHED AT VOLTAGE PEAK)

The de-enrgization of a capacitor bank can also generate a hazardous voltage transient if circuit breaker restrikes. Hence capacitor bank de-enrgization requires a specially designed circuit breaker which should be restrike free [6].

Reactor is required in the power system to manage the voltage profile and power transformer is required to step up and step down the voltage. Shunt reactor switching at random instant gives rise to the inrush current with high DC offset as shown in Figure 5 and opening can lead to re-ignitions and hence overvoltage. Similarly unloaded transformer energization gives rise to high inrush current.

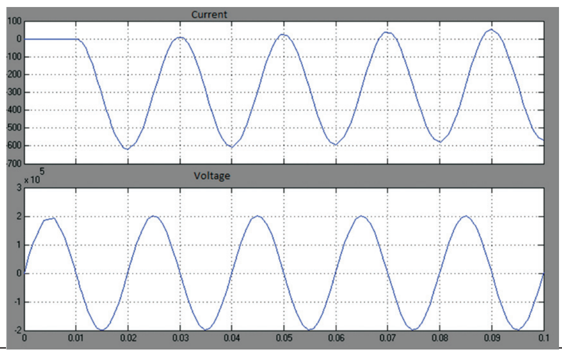

FIG. 5 REACTOR CLOSING CURRENT (WHEN SWITCHED AT VOLTAGE ZERO)

Reactor de-energization gives rise to re-ignition over voltages if switched inside the re-ignition window. This overvoltage can damage the reactor insulation [9]. Same kind of phenomena can be observed in case of interruption of unloaded power transformer. Low magnetizing current interruption and the inrush current interruption can create the chopping overvoltages and re-ignition overvoltages which are hazardous for the transformer insulation [10-12]. Same as this the energization transient in case of reactor and unloaded power transformer is harmful for the breaker as well as for the reactor and transformer [13-14].

Unloaded transmission line energization produces the overvoltages and inrush currents in the system [2]. These are hazardousfor power system equipments.The example of random energization of unloaded transmission line is shown in Figure 6.

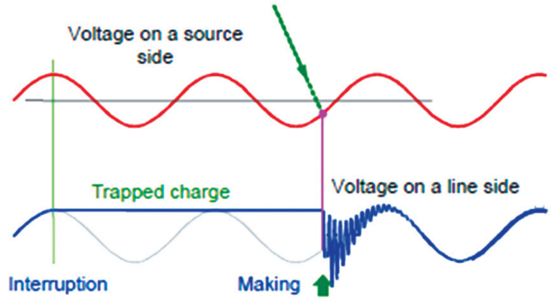

FIG. 6 RANDOM ENERGIZATION OF UNLOADED TRANSMISSION LINE[74]

Lot of researchers have reported the transient analysisand calculation methods which can predict the severity of the transients well before the damage to the power system equipments [15-21]. This is helpful for designing different mitigation devices and techniques like, surge arresters, pre-insertion resistors, pre insertion reactors,opening resistors, controlled switching system, etc.

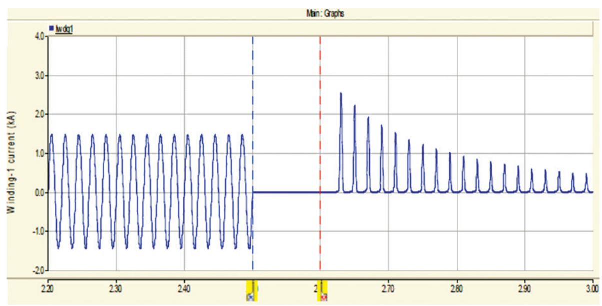

FIG. 7 RANDOM ENERGIZATION OF UNLOADED POWER TRANSFORMER [75]

3.0 CONTROLLED SWITCHING ASPECTS

There are many ways to mitigate switching transients like using pre-insertion resistors, strengthening the primary equipment itself , use of surge arrestors and the most recent methodology is controlled switching of circuit breakers.

The problem with the insertion resistor switching is that, the resistor has to be designed for the thermal and dielectric withstand capability. It is a costly component due to specialized manufacturing process. Strengthening the primary equipment is a costly option again. Surge arrestors can be used, but the mounting arrangements and the specialized design is involved in the same. Hence as compared to all these conventional options controlled switching is economical and technically viable option.

CIGRE committee has reported the substantial work in the area of controlled switching. State of the art survey conducted by CIGRE gives the basic requirements to be fulfilled for the success of controlled switching [22] [26]. The feasibility study gives the accuracy band requirements for the various load applications [23]. Overall execution of the controlled switching is summarized in the steps of planning, specifications, testingand guide for various application of controlled switching system [24] [25]. Benefits of controlled switching are elaborated in terms of breaker life and the cost factor [27] [28]. Controlled switching also gives benefit in power quality improvement [29].

There are various other papers from IEEE transactions and conference which gives the specific examples of development of controlled switching system and implementation of the same in the field [30-39].There are various challenges in the controlled switching system development. Making circuit breaker suitable for controlled switching is one of the biggestchallenges. Then development of electronic controller which should work in the high voltage environment is also a tough task. Reliability of the electronic controller is required to be tested properly before putting the same in the field.

4.0 CONTROLLED SWITCHING OF SHUNT CAPACITOR BANK

As discussed in above section the capacitor bank switching transient mitigation is the need of power system. Various methods are evaluated like insertion elements, surge arrestors, controlled switching for the switching transient mitigation [40]. Controlled switching is the economical and technically viable solution for the same. Controlled capacitor bank opening requires maintaining the higher arcing time and hence the higher contact distance in breaker at the time of recovery voltage application [41]. Lot of work related to controlled capacitor bank switching has been reported wherein simulations, factory and field testing, problems encountered are discussed in detail [42-47].

Major challenge in capacitor bank energization is the accurate prediction of the RDDS. The suitability of the circuit breaker for capacitor bank energization is decided by the RDDS and the mechanical scatter.The controlled energization of capacitor bank is shown in Figure 8.

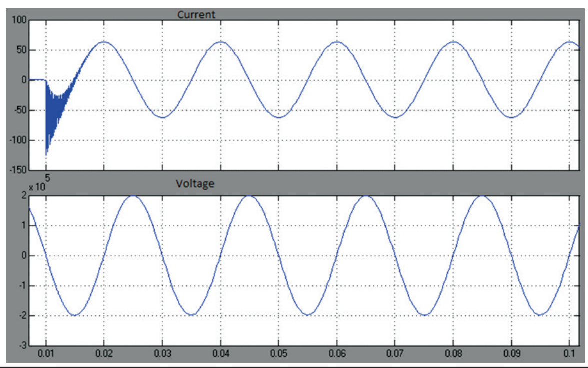

FIG. 8 CONTROLLED ENERGIZATION OF CAPACITOR BANK

5.0 CONTROLLED SWITCHING OF UNLOADED TRANSMISSION LINE

Unloaded long transmission line is very much capacitive in nature due to which the energization of the same gives rise to overvoltage and inrush current. Overvoltage severity depends on the line length. When the line has shunt compensation reactors, the capacitances of the transmission line oscillate with the inductance of the reactors during the auto-reclosing cycle. The main frequency component of the line voltage oscillation is lower than the power frequency (typically between 30 Hz and 45 Hz) and it is dictated by the degree of compensation of the line [48].Controller development for compensated line switching is really a challenging task [49].

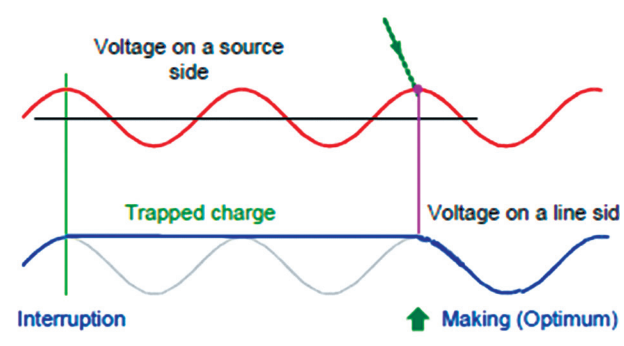

FIG. 9 CONTROLLED ENERGIZATION OF UNLOADED TRANSMISSION LINE[74]

Power quality can be improved substantially with the controlled switching technique [50]. Researchers have reported the work executed for actual implementation of controlled line switching and simulation part of it [51-53].

There is a major challenge in this, regarding the voltage waveform capturing by the controller. As this is not a power frequency waveform, the normal CVT can not be used. The voltage zero or voltage min detection is totally depends on the voltage capturing accuracy. Hence the controllers installed for line switching are very few, i.e. 1% as reported by the CIGRE survey [74]. The example of controlled energization of line is shown in Figure 9.

6.0 CONTROLLED SWITCHING OF SHUNT REACTORS

Shunt reactor is the essential component in the power system to manage the reactive power and voltage profile. Hence energization and de-enrgization of the shunt reactor is a frequent operation. Closing shunt reactor at voltage peak and opening the same in re-ignition free window are the optimum switching instants. The waveform of closing current is shown in Figure 10.

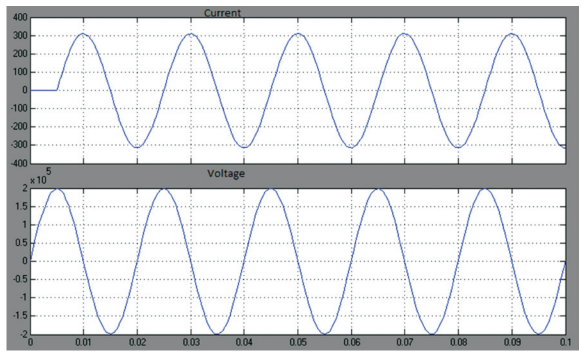

FIG. 10 CONTROLLED ENERGIZATION OF SHUNT REACTOR

Authors have reported the work related to controller development for 735kV reactor and successful testing of the system [54].Simulation work related to the optimum instant for shunt reactor switching also has been published [55] [56].

Shunt reactor closing is challenging task.Accurate prediction of RDDS and hence the prearcing time is the main requirement in this. To achieve the voltage peak as a making instant, controller should know what is the closing time and pre arcing time.

7.0 CONTROLLED SWITCHING OF UNLOADED POWERTRANSFORMER

Unloaded transformer is inductive in nature. If the transformer is closed at voltage zero then it will take a very high inrush current as the transformer core goes into saturation.These currents have undesirable effects, including potential damage or loss-of-life to the transformer, protective relay misoperation, and reduced power quality on the system.

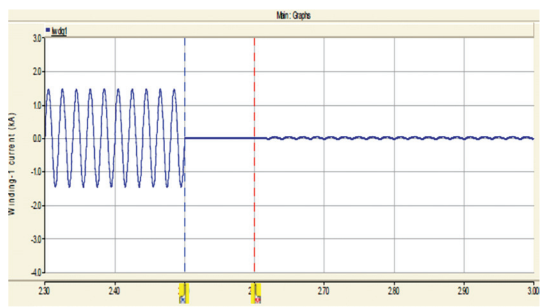

FIG. 11 CONTROLLED ENRGIZATION OF UNLOADED POWER TRANSFORMER[76]

Transformer controlled closing can be done in various ways, like with consideration of the residual flux, without consideration of residual flux, delayed closing so that the flux will get decayed [57]. The residual fluxmagnitude changes in case of transformers equipped along with circuit breakers with grading capacitors; hence measurement system will be required to capture the residual flux before controlled energization [58][59]. Artificial neural network with harmonic index evaluation approach is applied to find the optimum transformer energizing instant in real time [60]. Transformer controlled switching implementation with the consideration of mechanical scatter and rate of decay of dielectric strength of the circuit breaker gives the controlled closing success [61].There is a methodology reported for voltage applied on the transformer just before de-enrgization can be utilized for the residual flux prediction while energization [62].

Unloaded transformer energization has got a challenge of the residual flux measurement. Manufacturers have come up with the residual flux sensors which can be directly used with the transformer bushing tap for the flux measurement [70]. The sample waveform of controlled energization of unloaded power transformer is shown in Figure 11.

8.0 CONTROLLED FAULT SWITCHING

Controlled fault interruption objective is to limit the arcing time always to a minimum arcing time. This can give huge benefit for circuit breaker interrupter life enhancement. This is the area, where in very few researchers have worked. It is very difficult to predict the current zero properly, if the fault current waveform is of unsymmetrical nature then, the arcing time prediction will go wrong [22]. There is a work published wherein the author has given a method for fault controlled switching for single phase systems [63].

A new methodology of controlled fault interruption by intelligent circuit breaker is reported [64]. Where the moving speeds are adjusted according to the system fault requirements and simultaneously the arcing times can be controlled.

9.0 CONTROLLER DEVELOPMENT

Controller is the key component of the controlled switching system. Controller shall fulfill the requirements like working in the high voltage environment, reliable operation in severe environmental conditions when placed in the field. Controller consists of a power supply unit, microcontroller, analogue inputs i.e. CT and PT, sensor inputs, digital inputs for circuit breaker feedbacks, digital outputs for alarms and annunciation signal. There are many controllers available in the market which have key features like control voltage compensation, air pressure compensation, SF6 gas pressure compensation, idle time compensation, adaptive control for the closing time , making time [65-69].

There is a controller available with the residual flux measurement sensor for the unloaded power transformer energization[70].

The author has reported the work done for the controller development for line and transformer application [71].

10.0 RDDS PREDICTION IN SF6 GAS CB

Success of controlled making in case of capacitor, line, reactor and transformer is very much dependent on the accurate prediction of rate of decay of dielectric strength. RDDS can be either calculated or measured in the testing. Researchers have reported the work done in the RDDS measurement and the effect of short circuit currentinterruption on the reduction of RDDS [72]. The work suggests that there is 14% reduction in RDDS after 10 nos. load current interruptions. This may not be significant for the targets near voltage zero but it should be considered for the targets at voltage peak, i.e. for reactor and transformer energization.

There are various methods addressed for the making instant measurement like voltage dip sensing through wavelet transform with adaptive control [73], CT current initiation, electromagnetic field sensing [73], and prestrike voltage measurement

[29]. In case of already installed circuit breakers it is a real challenge to know the RDDS. In this case these making instant measurement techniques help to decide circuit breaker suitability for the desired controlled switching application.

11.0 DISCUSSION

Controlled switching success in case of closing application is solely depends on the accurate prediction of the making instant. The making instant prediction is nothing but the RDDS relation with the applied voltage. There are various factors which can affect the making instant of circuit breaker, like SF6 gas pressure, closing velocity, short circuit interruptions (contact conditions), voltage distribution factor in case of multibreak circuit breaker. Literatures have reported the work done on the algorithm development for the RDDS prediction using adaptive control by various methods.CIGRE working group has recommended to measure the RDDS with various changes of SF6 gas pressures & after certain short circuit operations [25]. The consideration of all the above mentioned circuit breaker parameters which can affect the making instant are required to be addressed in the algorithm development. During closing operations if any condition like gas pressure changes or circuit breaker has to undergo any severe short circuit interruption then the making instant prediction may go wrong, if it is solely based on the adaptive concept. To improve the accuracy of the making instant prediction, consideration of all the above mentioned factors with adaptive control is the most appropriate method.Hence the further research work is carried out in this area.

12.0 CONCLUSION

There are various conventional methods for switching transient mitigation like, using pre-insertion resistors, pre-insertion reactors, opening resistors, surge arrestors, etc. Controlled switching is new method which is economical and technically viable solution. The effectiveness of controlled switching depends on several factors, the most important of which is the circuit breaker operating time consistency. Breakers with a minimum deviation in operating times (i.e. statistical scatter of main & auxiliary contact) are best suited for controlled switching applications. Accurate GCB characteristics establishment for all parameters which affect operating time is also one of the important factor for the success of controlled switching system. Determination of RDDS & RRDS to find out the optimum making & breaking instant of the GCB plays an important role in controlled switching implementation. Controlled switching of circuit breaker in EHV and UHV transmission system is very beneficial in increasing life expectancy of the circuit breaker as well as the load equipment.

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