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ANALYSIS OF SWITCHING SURGES GENERATED BY CURRENT INTERRUPTION IN AN ENERGY STORAGE COIL*

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Abstract

The paper presents an analysis of the transient voltages which are generated when the current in a large magnetic energy storage coil is interrupted by a dc vacuum circuit breaker. The effect of the various parameters in the circuit on the transient voltage is discussed. The self inductance of the dump resistor must be minimized to control the generated transient. Contrary to general belief, a capacitor across the coil is not an effective surge suppressor. In fact, the capacitor may excite oscillations of higher magnitude. However, a capacitor, in addition to a surge suppressor, may be used to modify the frequency components of the transient voltage so that these frequency components are not coincident with the natural frequencies of the coil. Otherwise, resonant oscillations inside the coil may attain damaging magnitudes. The capacitor would also reduce the steepness of the wavefront of the transient across the coil, thus reducing the nonlinear voltage distribution inside the coil.

Introduction

Insulation coordination for high power equipment is essential to prevent insulation failure in view of the cost of outage not only of the affected equipment but also of other associated equipment which may be indirectly affected. Insulation coordination consists of matching the insulation strength of an equipment with the protective characteristics of the surge arrester to obtain the optimal protective margin and noninterference with the system operating conditions. Insulation coordination is achieved in three steps:

1. Determine the transient voltage characteristics of the equipment,
2. Determine the severity of the anticipated transient voltage surges, and
3. Provide cost effective but reliable surge protective measures.

A 30 MJ superconducting magnetic energy storage (SMES) coil will be installed in the Bonneville Power Administration (BPA) electrical power transmission system to act as an alternate means of transmission line stabilization.[1] Insulation coordination of this SMES coil is of utmost importance.

Figure 1 shows the protective dump circuit of the SMES system. The 30 MJ SMES coil, L, is charged by two six-pulse converter bridges through a dc vacuum circuit breaker. The current through a superconducting coil is sometimes required to be interrupted, as in the case of the coil losing its superconductivity. In such cases, the dc circuit breaker is opened, the current through the coil is bypassed through the dump resistor, R, and the arc in the dc circuit breaker is interrupted by a counterpulse circuit containing a precharged capacitor, C. This process of current interruption by the dc circuit breaker would produce a transient voltage across the SMES coil. The objective is to limit the magnitude of such a transient voltage to a safe value, so that the SMES coil is not damaged.

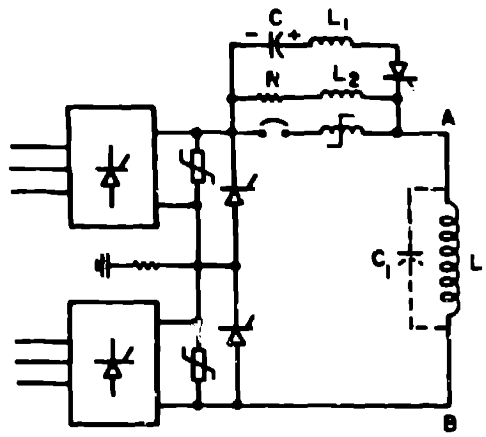

Fig. 1. Schematic of the protective dump circuit of the 30 MJ SMES system.
L = SMES coil, C_1 = capacitance across SMES coil, C = counterpulse capacitor bank, L_1 = waveshaping inductor for counterpulse circuit, R = dump resistor, L_2 = self inductance of R.

The analysis of the transient voltage generated by the opening of the dc vacuum circuit breaker is discussed in this paper. Alternate methods of protection of the SMES coil against transient overvoltages are also discussed. The transient voltage characteristics of the SMES coil are discussed in a companion paper.[2]

Method of Analysis

The current through the SMES coil is interrupted in the following sequence. The converter voltage is brought to zero, and the two series strings of thyristors of Fig. 1 are fired before the dc circuit breaker is opened. The precharged capacitor, C, is discharged through the arcing contacts of the dc circuit breaker by firing the thyristor in the capacitor circuit. This produces a sinusoidal current, the first half cycle of which is in the opposite direction to the flow of the circuit breaker current. The arc quenches when the instantaneous magnitude of this sinusoidal current becomes equal to the arc current, diverting the coil current through C and R. The resistance, R, is installed to discharge the stored energy in the coil after the current through the dc circuit breaker is interrupted. L_2 is the self inductance of the resistor R.

The transient voltage generated by this current interruption process will have two components. The first component is caused by the forced zero of current through the dc circuit breaker, and the second component by the residual voltage in the capacitor bank, C.

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Transient Voltage Caused by Forced Current Zero

The magnitude of the sinusoidal current during the discharge of the capacitor, C, is given by

$$I_c = I_{co} \sin \omega_o t, \tag{1}$$

where $I_{co} = V_c \sqrt{C/L_1}$,
V_c = capacitor precharge voltage, and
$\omega_o = 1/\sqrt{L_1 C}$.

By design, I_{co} is made greater than the SMES coil current, I_L, to insure current zero condition in the dc circuit breaker. If the arc is interrupted in a time period t_o, then

$$I_L = I_{co} \sin \omega_o t_o. \tag{2}$$

The analysis of recovery voltage caused by switch opening is generally made by injecting a current through the open switch, which is equal in magnitude but opposite in direction to the current being interrupted.[3,4] In this case, the magnitude of the injected current is

$$I_i = I_{co} \sin \omega_o (t_o + t) - I_L, \tag{3}$$

flowing in the same direction as the interrupted current, and t is the time after current zero in the dc circuit breaker. This is shown in Fig. 2. The recovery voltage component across the SMES coil, caused by current interruption, is then found by multiplying the injection current, I_i, by the impedance across the points A and B in Fig. 1. This component of the recovery voltage is given by

$$V_1 = V_c A_1 \left[\sum_{m=1}^{3} (\beta_m \cos \omega_o t_o - \omega_o \sin \omega_o t_o) \times (\alpha + \beta_m) \exp (\beta_m t) \times \prod_{n \neq m}^{1,..3} \{1/(\beta_m - \beta_n)\}\right], \tag{4}$$

where $A_1 = (LL_2)/A$
$A = LL_1 + LL_2 + L_1 L_2$,
$\alpha = R/L_2$,
β_m = roots of a cubic equation with coefficients a_o, a_1, a_2, a_3,
$a_o = R/(A \times C)$,
$a_1 = (L + L_2)/(A \times C)$,
$a_2 = R\,(L + L_1)/A$, and
$a_3 = 1$.

Transient Voltage Caused by Capacitor Residual Voltage

The residual voltage, V_{co}, of the counterpulse capacitor, C, at arc extinction is found as follows.

$$\begin{aligned} V_{co} &= Q_c - \int_0^{t_o} i\,dt/C \\ &= V_c - (1/C) \int_0^{t_o} V_c(\sqrt{C/L_1}) \sin \omega_o t\,dt \\ &= V_c \cos \omega_o t_o. \end{aligned} \tag{5}$$

This voltage is impressed across the circuit of Fig. 1 when the arc across the dc circuit breaker is quenched. The voltage across the points A and B is found by the equation,

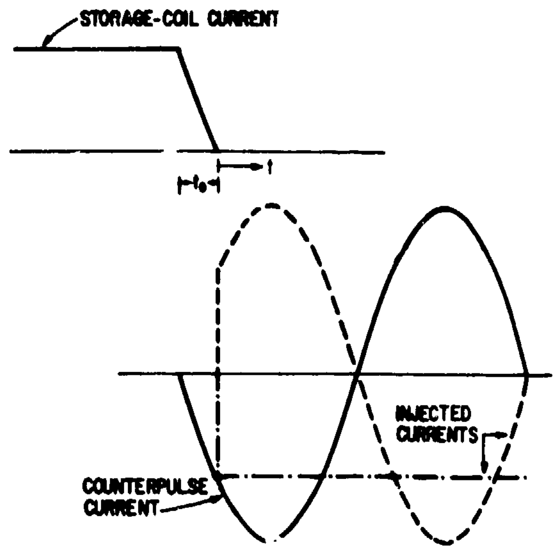

Fig. 2. Relationship among various current components during current interruption in SMES coil.

$$V_2 = V_c A_1 \cos \omega_o t_o \left[\sum_{m=1}^{3} \beta_m(\alpha + \beta_m) \exp (\beta_m t) \times \prod_{n \neq m}^{1,..3} \{1/(\beta_m - \beta_n)\}\right]. \tag{6}$$

The total voltage across the SMES coil is

$$\begin{aligned} V &= V_1 + V_2 \\ &= V_c A_1 \left[\sum_{m=1}^{3} (2\, \beta_m \cos \omega_o t_o - \omega_o \sin \omega_o t_o) \times (\alpha + \beta_m) \exp (\beta_m t) \times \prod_{n \neq m}^{1,..3} \{1/(\beta_m - \beta_n)\}\right]. \end{aligned} \tag{7}$$

This computation is valid when $C_1 = 0$. For finite values of C_1, the computation will be similar, except a fifth order equation will be introduced.

Computation

A numerical computer program was developed to solve equation 7. The voltage across the SMES coil, expressed as per unit of the counterpulse capacitor precharge voltage, is computed at time intervals specified by the user. Figures 3 through 5 show some of the examples of switching transient voltages across the SMES coil under various assumed conditions.

Discussion

Assumptions

The transient voltage across the SMES coil was calculated from the instant the current arc across the dc circuit breaker is quenched. The circuit breaker branch was assumed to be open thereafter. In practice, the open circuit breaker will act as a small capacitor, which will generate damped high frequency oscillations with the saturated inductance of the series connected

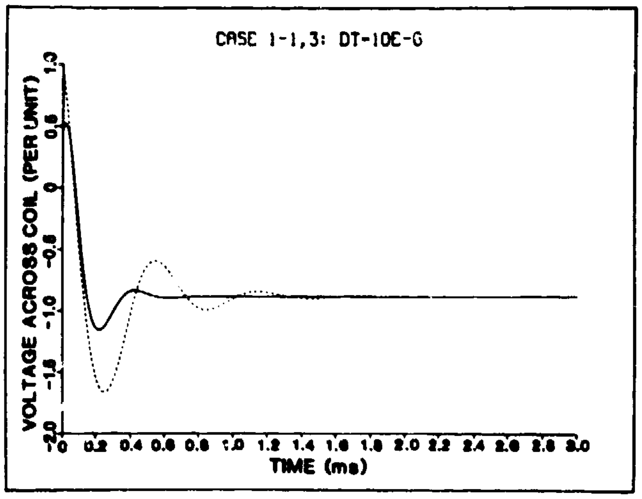

Fig. 3. Transient voltage across SMES coil caused by current interruption by dc circuit breaker: Effect of dump-resistor self inductance. V_c = 5 kV, I_L = 4.9 kA, L = 2.6 H, L_1 = 36 μH, C = 60 μF, C_1 = 0, R = 0.9 Ω. Solid curve: L_2 = 20 μH; Dotted curve L_2 = 100 μH. Per unit voltage = counterpulse capacitor precharge voltage, V_c.

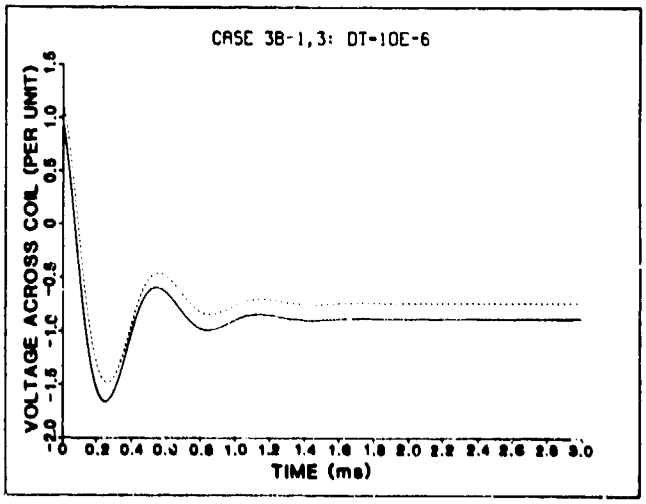

Fig. 4. Transient voltage across SMES coil caused by current interruption by dc circuit breaker: Effect of precharge voltage level of counterpulse capacitor. I_L = 4.9 kA, L = 2.6 H, L_1 = 36 μH, L_2 = 100 μH, C = 60 μF, C_1 = 0, R = 0.9 Ω. Solid curve: V_c = 5 kV, Dotted curve: V_c = 6 kV. Per unit voltage = counterpulse capacitor precharge voltage, V_c.

saturable reactor. This frequency was calculated to be about 14 MHz.

The analysis of transient voltage across the SMES coil was performed with the assumption that the counterpulse circuit was connected to the SMES coil directly. In the actual installation, the two will be separated by buswork. The effect of the bus inductance will be insignificant because of the high value of inductance of the SMES coil. The capacitance of the bus across the SMES coil would generate high frequency

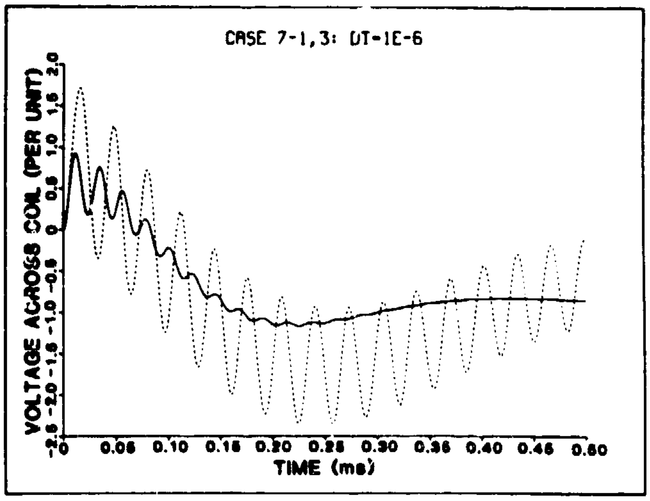

Fig. 5. Transient voltage across SMES coil caused by current interruption by dc circuit breaker: Effect of capacitance across coil. V_c = 5 kV, I_L = 4.9 kA, L = 2.6 H, L_1 = 36 μH, C = 60 μF, C_1 = 1 μF, R = 0.9 Ω. Solid curve: L_2 = 20 μH; Dotted curve: L_2 = 100 μH; Per unit voltage = counterpulse capacitor precharge voltage, V_c.

oscillations. Analysis showed that a 100 pF capacitance across the SMES coil generated a 3 MHz oscillation.

In the analysis, the thyristor string in the counterpulse circuit was replaced by a mechanical switch which conducts current in both directions. Although high frequency oscillations will be transmitted through the RC snubber circuit across the thyristor string, the low frequency oscillations will be cut off when the thyristor string shuts off near the current zero. Computation of the thyristor current showed that it goes through zero at about the negative peak of the voltage across the SMES coil.

Parametric Effects

Several parameters were varied to determine their effects on the transient voltage across the SMES coil. Figure 3 shows the effect of the self inductance, L_2, of the dump resistor R. Higher self inductance of R would increase both the positive and negative peaks of the transient voltage. The transient voltage is very sensitive to this parameter. Therefore, the dump resistor should be designed with the least possible self inductance.

Figure 4 shows the effect of the counterpulse capacitor precharge voltage level, V_c. The higher this voltage is, the higher would be the positive peak of the transient voltage across the SMES coil; the negative peak of the transient voltage is insensitive to V_c. In Fig. 4, the negative peak for V_c = 5 kV is higher than that for V_c = 6 kV. This is because the voltages are expressed in per unit. They are nearly equal when converted to kilovolts. The transient voltage across the SMES coil has two components as already mentioned. The first component is caused by the forced zero of current through the dc circuit breaker and the second component by the residual voltage in the counterpulse capacitor bank, C. The negative peak belongs to the first component, and the positive peak to the second component.

Figure 5 shows the effect of capacitance across the SMES coil. A capacitance across the SMES coil would produce oscillations. These oscillations are accentuated when the self inductance, L_2, of the dump resistor, R, is higher. This also would produce a higher peak voltage. The beneficial effect of C_1 is to reduce the slope of the front but not the amplitude of the positive peak as shown in Figs. 3 and 5. A steep front of the transient voltage could produce highly nonuniform voltage division within the coil with the possibility of turn to turn dielectric failure in the coil. The capacitor C_1 may also be used to modify the frequency components of the switching surge, so that these frequencies are not coincident with the natural frequencies of the coil; otherwise, internal overvoltages would be developed by resonant oscillations.

Effect of External Transients

Lightning strokes and switching surges on the BPA electrical transmission lines will generate traveling voltage waves which will eventually penetrate into the SMES coil. However, these voltage waves will be significantly attenuated by the transformers, and the surge arresters at the transformers and converters.

When lightning strikes the ground, electromagnetic fields are produced in its vicinity by the charge in the leader stroke and by the current in the return stroke of the lightning. These electromagnetic fields induce voltages across objects. Analysis of lightning induced votlage in a coil will be complex; however, because of its low voltage rating, a coil will be susceptible to damage from such voltages, particularly if installed outdoors and within a nonmetallic dewar.

Overvoltage Protection

The dump resistor will limit the voltage across the SMES coil, in addition to absorbing the energy stored in the coil. However, the self inductance of the dump resistor, unless low, would defeat the purpose of overvoltage protection.

A capacitor across the SMES coil would reduce the slope of the steep front of the transient. However, the subsequent oscillations might actually overstress the dielectric system of the SMES coil, as shown in Fig. 5.

The industry practice of transient voltage protection on rotating machines is generally to connect a surge arrester across the machine in addition to the capacitor across it. The capacitor reduces the slope of the voltage wavefront, and the arrester limits the peak value. However, a surge arrester, consisting of nonlinear resistors capable of dissipating 30 MJ of energy of the SMES coil, would be impractical.

An alternate approach would be to connect a stack of nonlinear resistors with low internal inductance across the dump resistor. The nonlinear resistors must be designed in such a way that most of the 30 MJ stored energy would be dissipated in the dump resistor. The nonlinear resistors would conduct only when the transient voltage exceeds a specified level, for instance 7.5 kV.

A possibility would still exist of resonant overvoltages internal to the SMES coil. If the applied switching transient contains a frequency component which coincides with one of the natural frequencies of the coil, the coil would oscillate at that frequency with a peak voltage which could be many times that of the applied voltage.[5]

The peak voltage of the internal resonant oscillations can be limited by installing properly designed nonlinear resistors at a few strategic places within the coil, such as between each end and the 1/4, 1/2, and 3/4 points along the winding, where the peaks of the first two space harmonics would occur. For superconducting coils this may be impractical because the elements will not function in liquid helium, and a number of leads would be required. In applications where the transient is generated within the system, such as the switching transient in the SMES system, the frequency component of the transient can be modified by installing a capacitor C_1 across the coil terminals, as shown by the oscillogram of Fig. 5. During internal resonant oscillations, the peak voltage is limited by the resistive elements within the coil. For a superconducting coil, the oscillatory current may be expelled from the superconductor to the surrounding cryostabilizer. An alternate method of damping the internal oscillations will then be to use the cryostabilizer as the damping medium, without compromising its stabilizing property. In this case, the transient analysis of the coil must be performed even before the cryostabilizer is designed.

Conclusions

Destructive transients might be impressed across coils during switching operations. The switching circuit must be designed with the objective of minimizing such transients. A significant parameter in the switching circuit is the dump resistor, which should be designed with the minimum possible self inductance.

A capacitor across the coil terminals by itself is not an effective protective device. A capacitor can be used to modify the frequency components of the switching surge so that these do not coincide with the natural frequencies of the coil. However, surge protective devices such as nonlinear resistors should be used, in addition, to limit the voltage peaks. The capacitor will also reduce the slope of the wavefront of the transient across the coil, thus reducing the nonlinear voltage distribution inside the coil.

The technique of insulation coordination should be applied for reliable operation of the system.

Acknowledgments

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