Fault Current Limitation by a Transformer Type FCL Based on the Second Generation HTS Wires

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Abstract—**A transformer type superconducting fault current limiter (FCL) for electric power grids was developed utilizing a nonlinear resistor made of the second generation HTS wire. Using of the second generation HTS wire instead of the first one was found to reduce by an order the required amount of superconducting materials. Fault current limiting action and transients in an electric circuit with the prototype FCL have been studied. The effective limitation of peak and steady state fault current was demonstrated using the FCL. The physical basis of the FCL operation was investigated by studying a superconducting-to-normal transition in the second generation HTS wires.**

Index Terms—**high-temperature superconductors, fault current limiters, transformers, transient analysis**

I. INTRODUCTION

A transformer type fault current limiter (FCL) for ac electric power grids introduces significant inductance into the power system during a fault [1]. It virtually has no impact in a network under normal operating conditions inserting only low impedance until a fault event occurs. The basic component of the FCL is a series-connected transformer with the secondary side shunted by a nonlinear resistor. For the fabrication of such a nonlinear resistor superconducting materials are applicable. This type of a limiter allows the cryogenic environment to remain mechanically isolated from the rest of the circuit. Using of bulk HTS cylinders [2], [3] in the secondary circuit of the transformer enabled a three-phase shielded iron core FCL to be built, tested and installed in a power plant [4]. The first and second generation HTS wires can also be used in the current limiting transformer [5].

The second generation HTS wire is the YBCO coated conductor having the critical temperature of superconducting-to-normal transition of about 92 K and high normal state

resistivity. The superconductor heating and cooling governs the FCL response and recovery time respectively when a fault occurs and after the fault clearing [6].

In order to design a FCL with a proper set of characteristics a study was made of the fault current limiting action and transients in an ac circuit protected by the laboratory scale prototype FCL. The results of the experimental research are presented in this paper.

II. EXPERIMENTAL

To carry out the experiments the laboratory scale transformer type prototype FCL was designed and manufactured using a nonlinear resistor made from the YBCO coated conductor. Copper primary and secondary windings of the transformer had 80 and 1 turns respectively, and were mounted on the legs of a closed iron core of 55 mm in diameter. The secondary winding was made of a copper tape in the shape of a hollow cylinder with a longitudinal opening. The HTS resistor was made of a SuperPower 2G Stabilizer Free tape of 12 mm in width and 100 mm in length. It was connected across the secondary winding terminals and put in a plastic cryostat with liquid nitrogen. The critical current of the HTS wire is about 300 A at 77 K.

Fig. 1 shows a schematic of the ac circuit with the FCL used to study the transients and steady state modes after fault events. Commercial frequency ac voltage up to 50 V is
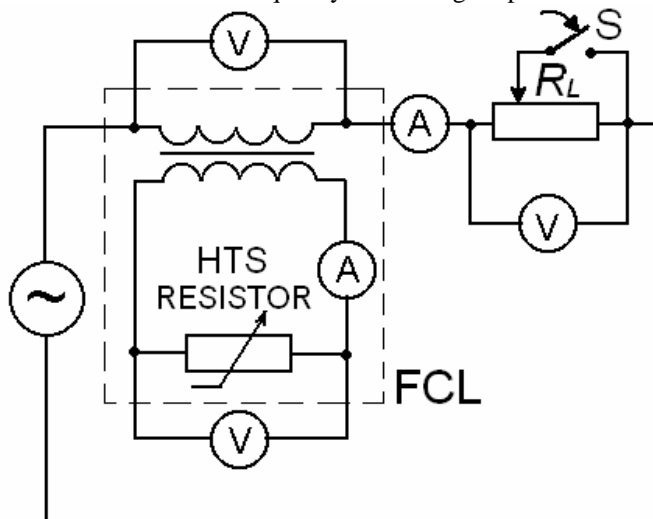

Fig. 1. Schematic diagram of the short-circuit test circuit with the transformer type FCL.

supplied to the circuit by an autotransformer. The FCL is connected in series to the protected circuit. The resistor $R_L = 10$ Ohm is a purely resistive external load. Closing of the switch S simulates the short circuit in the load or abrupt load current increase. Instantaneous voltage and current values across the elements of the circuit are registered every 0.05 ms.

III. RESULTS AND DISCUSSION

A. The FCL Voltage-Current Relationship

The ac voltage-current relationship of the FCL was measured in terms of the voltage and current peak values. The FCL input voltage is identical to the voltage across the primary terminals of the transformer. The current in the circuit passes through the transformer primary winding. The results of the measurements are shown in the *I-V* plot (Fig. 2). The relationship was found to consist of two steady state portions denoted as OA and BC, and a non-stationary portion extended from point 1 to point 6 in Fig. 2. The points 1-6 have been determined from the voltage and current peak measurements in the quasi-steady state which takes place after the switch S closing and lasts until the superconductor quench. The arrows denote the transitions from the low impedance non-stationary states to the high impedance steady states.

B. Transition Process between the Low and High Impedance Modes of the FCL

Time resolved measurements of the transition processes denoted by arrows in Fig. 2 were carried out. Fig. 3 shows the envelopes of the FCL input voltage (a), the circuit current (b) and the HTS current (c). The arrows indicate the moment of time when a fraction of the load R_L is shunted by closing the switch S. This results in instant stepwise increase of the FCL input voltage, circuit current and superconductor current. The peak superconductor current becomes greater than the critical current of the HTS wire. Therefore this state of the superconductor is unstable and lasts for the period of time required the HTS temperature to exceed the critical one. This state is represented as point 1 in Fig. 2. In 1600 ms after the closing of the switch S the superconductor goes normal. As a result the transition occurs from the low to high impedance
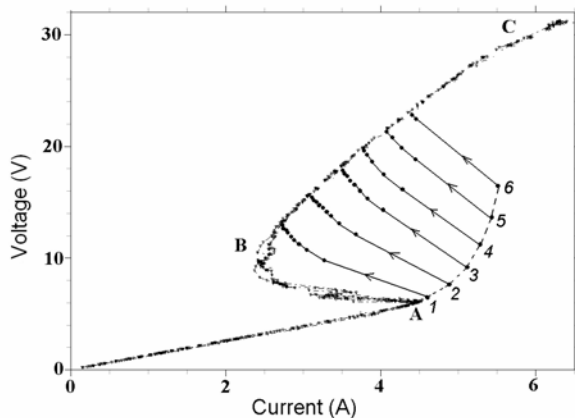

Fig. 2. *I-V* curve for the transformer type FCL. The OA and BC lines represent the steady state modes. The points 1-6 denote non-stationary states of the FCL.
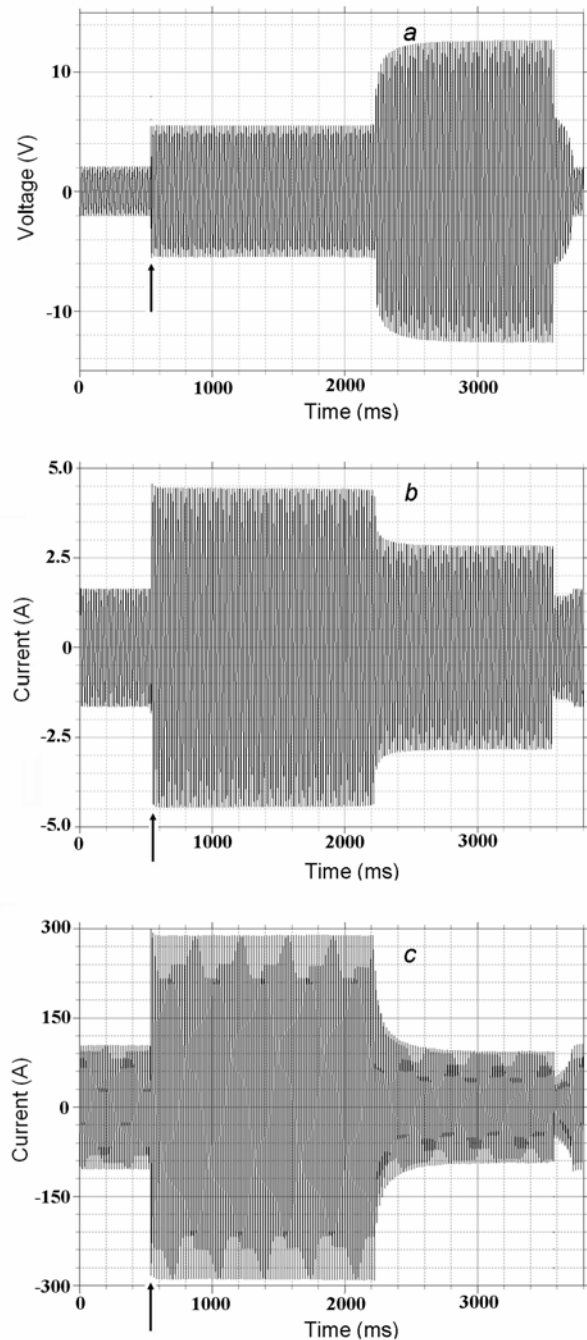

Fig. 3. The FCL input voltage (a), circuit current (b), and HTS resistor current (c). The waveforms show the transients after the transition starts from the point 1 of the *I-V* curve.

mode of the FCL (see Fig. 2), the input voltage increases and both the circuit and superconductor currents decrease. After the opening of the switch S the FCL recovery takes place during the period of time required to re-cool the HTS wire and this is also shown in Fig. 3.

The duration of the non-stationary state becomes shorter as the magnitude of the initial voltage step increases, i.e. from point 1 to point 6 in Fig. 2. At point 6 the time delay between the voltage step and the transition to the high impedance mode is about half the first cycle. At a greater voltage step the transition time amounts to a small fraction of a cycle therefore

the FCL response time is sufficiently small to limit the peak fault current.

C. Superconducting-to-Normal Transition in the HTS Nonlinear Resistor

The processes in the HTS nonlinear resistor were investigated by means of potential probes connected to the YBCO coated conductor. The inset in Fig. 4 shows the probe positions on the conductor surface. V_2 denotes the voltage across the transformer secondary terminals, which is identical to the voltage across the HTS resistor, and V_{HTS} is the voltage measured in the middle portion of the superconductor. The voltage drop across the contact between the YBCO coated conductor and copper lead is denoted as V_{cont}. The waveforms of the three voltages measured in the current limiting mode of the FCL operation are shown in Fig. 4. The arrow indicates the moment of time when the switch S closes. Prior to this moment the voltage waveforms are sinusoidal with very low amplitudes. When a portion of the load R_L is shunted by the switch S the voltages increase and their waveforms become nonsinusoidal. A peak arises every half-cycle due to the resistive state of the HTS (the flux-flow resistance) which originates from the supercritical current flowing within a fraction of a cycle. The heat production in the resistive state enforces the superconductor temperature to increase. Due to the normal zone propagation [7] and heat transfer to liquid nitrogen it takes certain time for the superconductor to go normal. Under the circuit conditions that took place while the waveforms in Fig. 4 were recorded the required time was about five cycles. After the superconductor goes normal the transformer operates as a constant voltage source, thus $V_2 = V_1/K$, where V_1 is the primary voltage and K is the turns ratio. Because of the high normal resistance of the coated conductor the secondary current flowing through the HTS resistor becomes less than the critical current. Combined with the high heat capacity of the massive copper leads, this results in cooling of the HTS-copper contact area below the critical temperature, so the magnitude of V_{cont} decreases to zero (see Fig. 4). Therefore the quench is not homogeneous, the normal zone being located in the central part of the HTS tape. All the described processes take place while the initial condi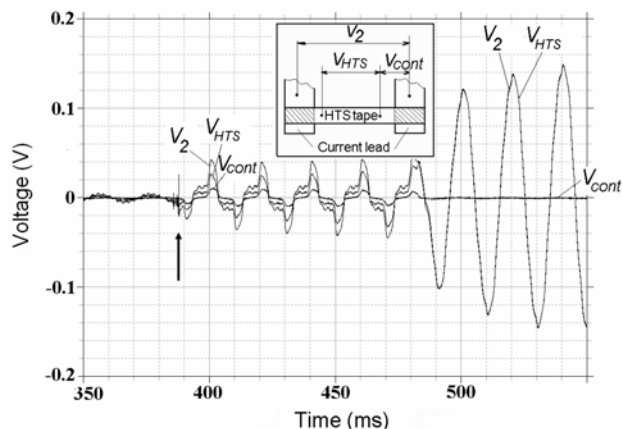tions after the closing of the switch S fall into the transition region in Fig. 2. This is not the case when the load R_L is short-circuited and the transition lasts less than half the first cycle.

D. Transients at Fault

To study transients at fault in the FCL protected circuit the load R_L is short-circuited. The normal operation mode primary voltage and current before the fault are set somewhere in the OA portion of the *I-V* curve. After the fault the steady state voltage and current become as high as the values in the vicinity of the point C in the BC portion of the curve. To investigate the FCL recovery under load and subsequent recurring current limiting action the switch S operating sequence was used to be "close-open-close".

Fig. 5 shows envelopes of the voltage across the FCL input terminals (Fig. 5(a)) and current in the circuit (Fig. 5(b)) when such an operating sequence takes place. The processes in the circuit under the normal operation, fault event, and recovery are denoted in Fig. 5 as Normal, Fault, and Recovery respectively. When the fault occurs the FCL input voltage increases by an order and the current transients take place. The peak fault current is about 4 times greater than the normal current amplitude and the steady state fault current is 2 times of the normal one.

After the fault clearing the external load returns to its initial value R_L. But the input FCL voltage is still greater and the
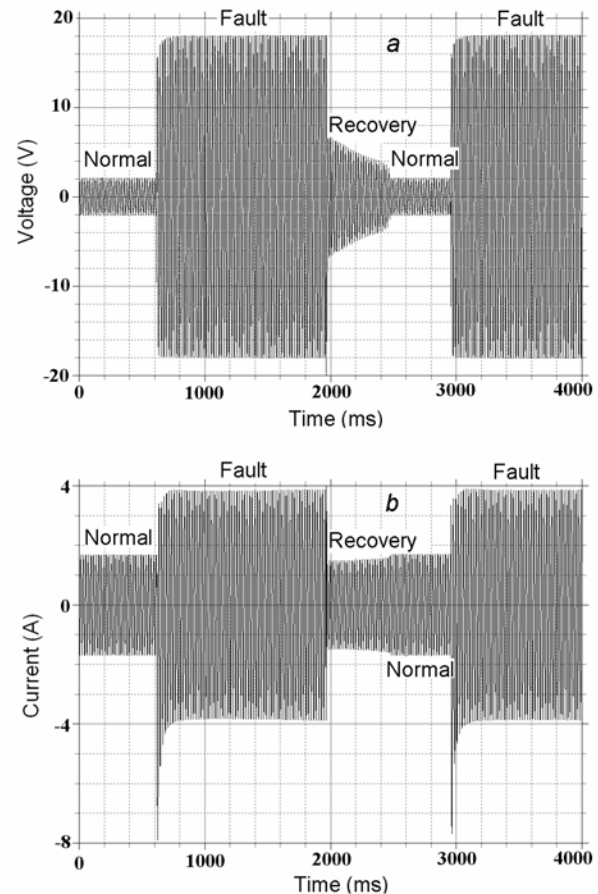

Fig. 5. Voltage (a) and current (b) waveforms in normal, fault limiting, and recovery conditions.

Fig. 4. Voltage waveforms across the HTS resistor (V_2), the central portion of the HTS coated conductor (V_{HTS}), and the HTS-copper contact (V_{cont}).

circuit current is less than the normal voltage and current respectively. This is due to the FCL recovery under load period of time lasts for about 0.4 s. Fig. 5(b) shows that after the recovery process is over one more fault current is limited.

Fig. 6 immediately indicates the limiting of a peak fault current by the FCL. The fault event takes place at a zero voltage (Fig. 6(a)), which would result in the largest magnitude of the peak prospective fault current. Fig. 6(b) shows the fault current transient waveform. When the fault occurs the current increases but the incipient fault current is limited in less than 2 ms owing to the quenching action of the superconductor. Due to high inductive reactance of the FCL in the limiting mode both peak and steady state fault currents are limited to 20% of the prospective fault current. The FCL withstands a fault of any duration.

E. Enhancement of the FCL Initiating Current

To trigger the FCL fault response the circuit current should exceed the FCL initiating current. The transformer type FCL initiating current is given by $I_{init} = I_c/K$, where I_c is the critical current of the HTS conductor connected to the transformer secondary terminals. Connecting the HTS wires in parallel can provide the FCL initiating current enhancement. Fig. 7 shows the I-V curves for the FCL with one and two YBCO coated conductors in parallel. The FCL initiating current doubles as a result of two-time increase of the HTS conductor current capacity.

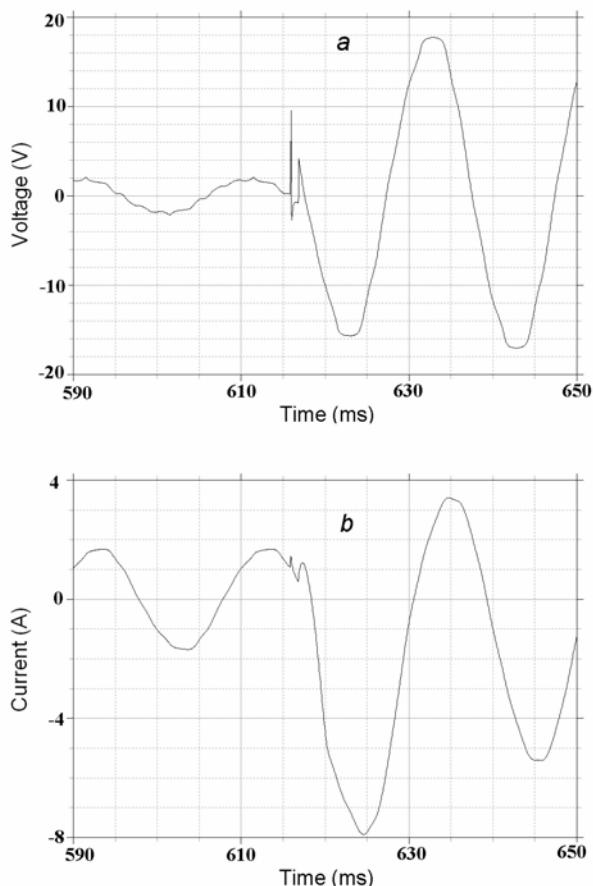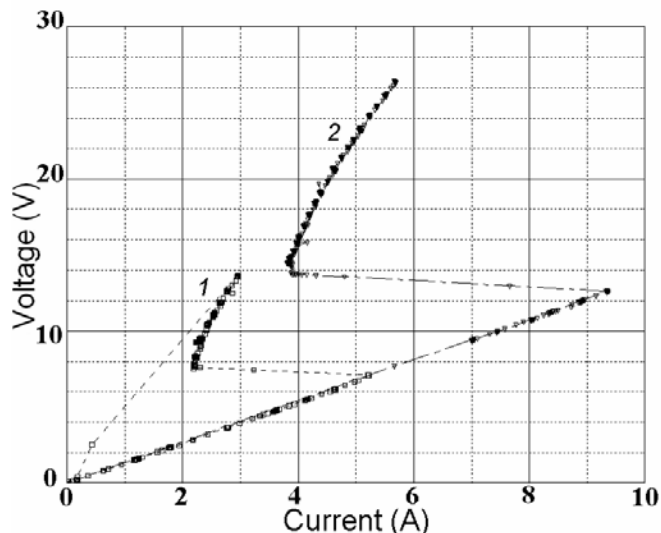The laboratory scale prototype FCL impedance in normal

Fig. 7. I-V curves for the transformer type FCL with one (1) and two (2) HTS coated conductors in parallel.

operating mode is found to be near 1 Ohm (see Fig. 2, Fig. 7). This is due to the transformer leakage impedance of 20% originating from the small iron core diameter. For a large scale device the leakage impedance less than 5% is expected [5].

IV. CONCLUSION

An experimental study was made of fault current limiting action and transients in an electric circuit with a small scale transformer type prototype FCL. The YBCO coated conductor was used as a nonlinear resistor connected across the transformer secondary terminals. The FCL demonstrates high performance characteristics in limitation of the peak and steady state fault current. The response time is less than 2 ms and the recovery-under-load time is less than 0.5 s. The prototype FCL is not damaged while limiting the peak and steady state fault current of any duration.

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Fig. 6. Voltage (a) and current (b) waveforms during a fault event.