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FUZZY LOGIC CONTROLLED SERIES TRANSFORMER BASED FAULT CURRENT LIMITER

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ABSTRACT
A novel fuzzy logic controlled transformer-based solid state fault current limiter (TBSSFCL) for wind generation. The proposed TBSSFCL is capable of controlling the magnitude of fault current. In order to control the fault current, primary winding of an isolating transformer is connected in series with the line and the secondary side is connected to a reactor, paralleled with a bypass switch which is made of anti-parallel insulated gate bipolar transistors. By controlling the magnitude of ac reactor current, the fault current is reduced and voltage of the point of common coupling is kept at an acceptable level. Also, by this TBSSFCL, switching overvoltage is reduced significantly. The solid state switches are controlled with the help of fuzzy logic controller in this work. The fuzzy logic is a heuristic controller which can accurately control the operation of IGBT in this propose system The proposed TBSSFCL can improve the power quality factors and also, due to its simple structure, the cost is relatively low.

I – INTRODCUTION

Developing power system networks and their interconnections may increase the short-circuit levels beyond the capacity of circuit breakers (CBs). Short-circuit fault can cause overvoltage transients, loss of synchronization, and isolation failure and may cause explosion of equipments containing insulating oil. There are solutions such as upgrading or replacing switchgears, which are expensive.

Distribution network protection mainly relies on proven protection devices such as fuse. This equipment is a self-triggering, cheap, small size, and reliable protective device which can interrupt fault currents without using sensors and actuators. But, it is a single-use device and needs manual replacement. Employing high impedance transformer to increase the fault circuit impedance is another solution, which causes additional network losses and needs redesign for maintaining the voltage profile. CB is also a protective device, which can be tripped and reset manually or automatically. However, CBs with high-current interrupting capability are expensive electromechanical systems. Replacement of protective CBs is a costly solution to cope with rising fault current levels. In recent years, a novel scheme for limiting the magnitude of fault current, the so called “fault current limiter” (FCL), has been proposed and used as the best solution. This scheme can limit the fault current, dismissing the costly upgrade of switchgears. FCLs application in distribution networks not only suppresses the fault current and limits the inrush current, but also improves the transient stability, power quality, and reliability. Development of various types of FCLs has been conducted for many years by many research institutions around the world. Solid-state FCL (SSFCL) is a power electronic-based device with fast response in fault current limiting. SSFCLs have been classified into three major groups: 1) the series switch (mechanical or semiconductor) ; 2) the bridge ; and 3) resonant structure types. A single-phase FCL employing insulated gate bipolar transistor (IGBT)-based bidirectional switch can be realized by using a stack of IGBTs, an anti-parallel diode, and varistors connected in parallel with the switches for voltage clamping. Bridge-type FCLs with reduced number of controlled devices have been presented in, in which single-phase and three-phase four-wire configurations have been proposed. Its fast response allows the cost, weight and volume of the reactor to be reduced. The effect of controllable resistor type FCL on voltage sag and fault current has been studied in, where a damping resistor is inserted into the transmission line, via IGBT switch and isolation transformer. The suggested structure can improve the voltage profile up to an acceptable level, but overvoltage on the IGBT is considerable. Application of superconducting FCL (SFCL) in loop power distribution systems for voltage sag analysis has been considered in. In order to overcome the problems raised by distributed generation (DG), static FCL (SFCL) has been proposed in. SFCL can decrease fault current level and improve power quality during fault. In addition, FCL effect on the distribution

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networks protection in the case of installed DG has been studied in. In a radial distribution network is considered for comparison of the performance of two SSFCLs, regarding the fault current and power quality. The effect of SSFCL on the fault current in a single-source radial system, as well as a multiple source distribution system with a bus-tie has been presented in. Study of electrical system with SFCL connected in series with the feeder has been performed in. This system uses fiber optic communication to coordinate the operation of fault interrupting switches, located along the circuit. A new hybrid type FCL topology for use in distribution systems has been proposed in. This project employs pulse-width modulation technique to control the fault current. Quantitative analysis for FCLs, high temperature superconductor cables and transformers, in the world market, has been made in. Regarding their protective reaction, FCLs can be divided into two types. One type limits the fault current to an acceptable level, which can be safely interrupted by CB. The other type acts as a breaker and interrupts the fault current itself. In this project, the first type, i.e., non-interrupting FCL, is investigated. The proposed transformer-based solid state FCL (TBSSFCL) has a simple structure, which can limit the magnitude of fault current to some safe value. In addition to restoring the point of common coupling (PCC) voltage, it is capable of reducing harmonic distortion and switching overvoltage, as compared to the five newly proposed FCLs. The TBSSFCL operations in normal and faulty conditions are studied. An experimental prototype is also developed and tested, the results of which clearly confirm the simulation results. It is shown that the proposed TBSSFCL has a simple and cheaper structure, while acting better, as compared with the above mentioned FCLs.

II – RELATED WORK

A novel bridge–type fault current limiter (FCL) based on self-turnoff devices for three-phase power systems are proposed in [1]. Compared with the SCR-based bridge type FCL, the new one is smaller in size, better in dynamic performance, and simpler in control method and control circuitry. The novel FCL is composed of a rectifier bridge—a dc-limiting reactor and one/three bypass reactor/reactors—for a single-phase/three-phase structure. The increasing speed of the fault current just after the occurrence of a fault is limited by a dc-limiting reactor, whose inductance is designed according to the response speed of the control circuit.

In paper[2], the bridge type fault current limiter (FCL) with discharging resistor is used for solving these problems. For this FCL, a control scheme is proposed, which uses the dc reactor current as control variable, to adjust the terminal voltage of induction generator (IG) without measuring any parameters of system.In paper [3], to limit the fault current and restore the PCC voltage, the power quality improving function is proposed and integrated in the bridge type FCL. This function is realized by a resistor and parallel switch which are in series with DC reactor. It is shown that controlling turn on and turn off duration of switch, can not only limit the fault current but also restore the voltage of PCC during fault.A diode-bridge-type non-superconductor fault current limiter (NSFCL) is proposed by Mehrdad Tarafdar Hagh et al.,. The structure has the capability of controlling the dc reactor current that yields to control the magnitude of fault current. In order to control the magnitude of dc reactor current, a discharging resistor is used in the proposed structure. By controlling the magnitude of dc reactor current, it is possible to reduce the current rating and inductance of dc reactor.

III – PROPOSED SYSTEM

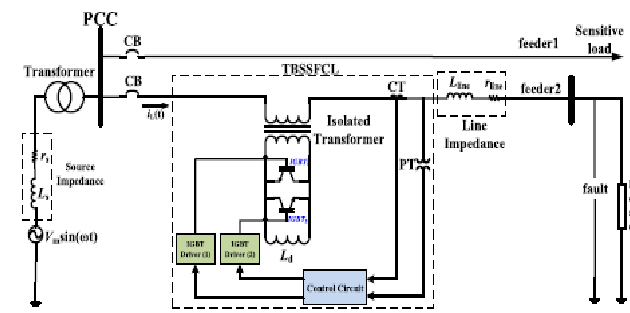

Figure 1: Single line diagram of a double feeder radial distribution network

A. During normal mode:

The IGBTs are on and hence the secondary of the transformer is short circuited and will lead to a minimum voltage drop across the line.

B. during Fault mode:

When fault current $I_F > I_L$ then IGBTs are turned off with the help of controller.

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This will open the secondary of the transformer and also adding the impendence in series with the feeder. Hence the fault current is minimized.

C. System operation:

Single line diagram of a double feeder radial distribution network, including the proposed TBSSFCL, is shown in Fig. 1. It is assumed that the feeder F1 supplies a sensitive load and the feeder F2 delivers power to other loads. The TBSSFCL is composed of three main parts as described below. An isolating transformer with unity turn ratio, the primary winding of which is connected in series with the line. The secondary winding of this transformer is connected to an anti-parallel IGBTs switch in parallel with a non-superconductor (copper) coil which serves as an ac reactor, modeled by *Ld* in Fig. 1. The parallel connection of IGBTs and ac reactor forms a fault current amplitude controller and, together with the series transformer constitute the TBSSFCL.

D. Tbssfcl Operation Principles:

In normal operation mode IGBTs are on, so the secondary winding is short circuited and there is negligible voltage drop on primary side of the transformer. In this case, TBSSFCL shows negligible impedance and has little effect on power quality. At fault inception, monitoring system recognizes the fault and turns off the anti-parallel IGBTs. Therefore, the bypass path is removed and the secondary circuit is closed through the ac reactor. This results in increased impedance of the TBSSFCL, which limits the fault current to some acceptable level.

E. Circuit operation:

The value of the feeder current, TBSSFCL operates in two modes. In normal operation mode, when the system operates at steady state, as well as at the fault inception, that the fault current is less than a pre- specified value *IL*, IGBTs are on, causing a voltage drop in the order of a few volts In addition, the series transformer would not normally have leakage impedance of more than 3–4%. Therefore, the total voltage drop across the TBSSFCL would be negligible and is not taken into account, in this project. The other mode corresponds to the fault condition, when the feeder current exceeds *IL*. In this mode, IGBTs are in off state and the fault current is limited by TBSSFCL. During the normal mode, ac reactor current is zero and the line current is given by

$$V_m \sin(\omega t) = L\frac{di_L(t)}{dt} + Ri_L(t) \qquad (1)$$

Where *R* and *L* include the source, line, and load resistances and inductances and the source voltage of the electrical network is assumed sinusoidal. In this case, the system is in steady state, i.e., the transient component of current has already been damped. Therefore, the solution of (1) is as given in

$$i_L(t) = \frac{V_m}{\sqrt{R^2+\omega^2L^2}} \sin\left(\omega t - \tan^{-1}\frac{\omega L}{R}\right). \qquad (2)$$

In fault condition, the line current increases rapidly and exceeds *IL*, by which the controller turns-off the anti-parallel IGBTs and connects the ac reactor to the feeder. During fault mode, the ac reactor charges according to (1), but with the values of *L* and *R* including TBSSFCL inductance and resistance and excluding the short circuited load parameters. Solving (1) for the fault condition yields

$$i_L(\omega t) = Ae^{-\frac{R}{L\omega}\omega(t-t_1)} + B\sin(\omega t - \varphi) \qquad (3)$$

Where,

$$\left\{A = \frac{-V_m}{\sqrt{R^2+\omega^2L^2}},\ B = \frac{V_m}{\sqrt{R^2+\omega^2L^2}},\ \varphi = arc\tan\left(\frac{\omega L}{R}\right).\right.$$

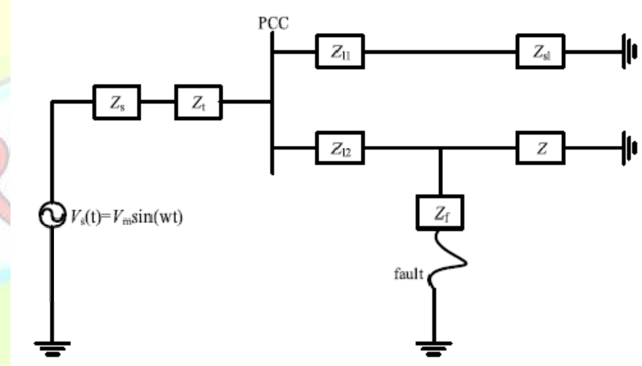

Figure 2. Positive sequence equivalent circuit of the radial distribution network

Equation (3) is composed of exponential and sinusoidal terms. The exponential term indicates a transient in the line current, duration of which (from *t*1 to *t*2 in Fig. 6) depends on the system time constant (*Ld*/*R*), where *R* is the system resistance seen by the ac reactor.

F. Control System:

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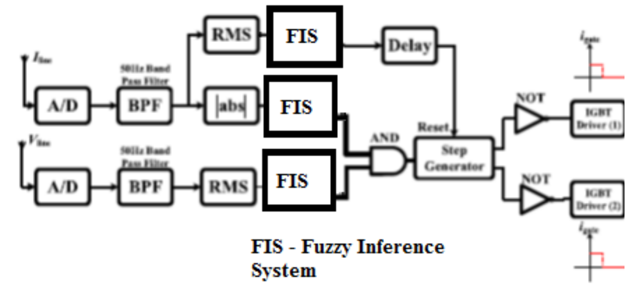

Figure 3. Control system block diagram.

Control block diagram of TBSSFCL is shown in Fig. 4. In order to control TBSSFCL, the line current (*i*Line) is sampled via a current transformer and is sent to the control circuit. Before comparing *i*Line with the maximum permissible current level (*IL*), it is passed through a 50 Hz band pass filter and its absolute value is sent to comparator (1). Monitoring the instantaneous value of line current increases the controller response speed to the fault occurrence. Also the line voltage (*V*Line) is measured through a potential transformer and its root mean square (RMS) value is compared with the reference value (*Vref*) in comparator (2). In this paper, *Vref* is set to 0.8 p.u., as it is required for motor starting and below this value motor cannot operate. In normal operating mode *i*Line and *iL*, and *V*Line and *Vref* are in marginal level and the step generator output pulses turn the IGBTs on. So, the secondary of isolating transformer is short circuited and TBSSFCL shows negligible impedance. At fault inception, as *i*Line exceeds *iL*, the control circuit detects abnormal condition. If the voltage control section also detects sever voltage drop, the step generator turns the anti-parallel IGBTs off and inserts the ac reactor into the current path, which increases the circuit impedance, resulting in fault current limitation. A third control loop can be formed by getting a feedback from the line current RMS value. The line current is applied to a RMS calculating block, the output of which is compared with the reference current level (*iR*). At the fault removal, while the anti-parallel switches are still OFF, the RMS value of line current decreases rapidly below the reference value *iR*. The detector circuit will then send the reset signal to the step generator block and this block

generates the co mand signal for IGBTs after a half cycle delay. As a result, the system returns to its normal operation mode and TBSSFCL switches turn on again. Combination of the three command signals (voltage, instantaneous current, and RMS current control loops), as the input signals to the step generator block, generates the appropriate drive signals for IGBTs. This control logic guarantees TBSSFCL proper operation during normal and fault conditions. It can also detect motor starting and transformer energization inrush currents, to prevent TBSSFCL malfunction. Although, TBSSFCL operation during motor starting and transformer energization can reduce over current amplitude and may have some advantages for distribution networks, however, it may increase the start time of motors.

G. Fuzzy Logic Controller Design

For implementing the control algorithm of a shunt active power filter in closed loop, the DC capacitor voltage is sensed and compared with a reference value.

The obtained error $e(n) = V_{dc,ref}(n) – V_{dc,act}(n)$

Change in error $ce(n) = e(n) – e(n-1)$

At the nth sampling instant are taken as inputs for the fuzzy processing. The control scheme is shown in Fig. 3. After a limit, the output of the fuzzy controller is considered as the amplitude of the reference current I_{max}. This current I_{max} takes care of the losses in the system and the active power demand of load. By comparing the actual source currents (isa, isb, and isc) with the reference current templates (isa*, isb*, and isc*) in the hysteresis current controller, the switching signals for the PWM converter are obtained [6]. After proper amplification and isolation, the switching signals so obtained, are given to switches of the PWM converter.

The internal structure of the fuzzy controller is shown in Figure 3. The error 'e' and change in error 'ce' are the real world numerical variables of the system. The following seven fuzzy levels or sets: NB (negative big), NM (negative medium), NS (negative small), ZE (zero), PS (positive small), PM (positive medium), and PB (positive big) are chosen to convert these numerical variables to linguistic variables as shown in Figure 4. The characterization of fuzzy controller is as follows: i. seven fuzzy sets for each input and output. ii. Triangular membership functions for simplicity. iii. Fuzzification using continuous universe of discourse. iv. Implication using Mamdani's 'min' operator. v. Defuzzification using the 'centroid' method.

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The elements of the rule base table are determined based on the theory that in the transient state, large errors need coarse control, which require coarse input/output variables and in the steady state, small errors need fine control, which require fine input/output variables. Based on this the elements of the rule table are obtained as shown in Table.1, with „e‟ & „ce‟ as inputs.

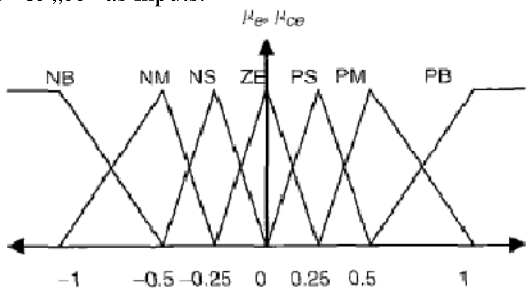

Figure 4 Input Membership function

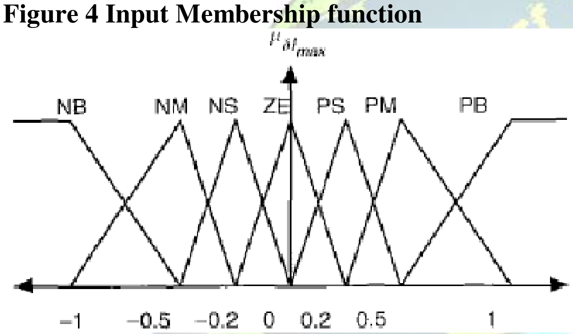

Figure 5 Output Membership function

Table1. Fuzzy rule table

e \ ce	NB	NM	NS	ZE	PS	PM	PB
NB	NB	NB	NB	NB	NM	NS	ZE
NM	NB	NB	NB	NM	NS	ZE	PS
NB	NB	NB	NM	NS	ZE	PS	PM
ZE	NB	NM	NS	ZE	PS	PM	PB
PS	NM	NS	ZE	PS	PM	PB	PB
PM	NS	ZE	PS	PM	PB	PB	PB
PB	ZE	PS	PM	PB	PB	PB	PB

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IV – SIMULATION RESULTS

The proposed system was implemented with the help of Simulink and sim power system tool boxes in the MATLAB R2013a software. The following figure represents the following figure depicts the power system network considered in this work.

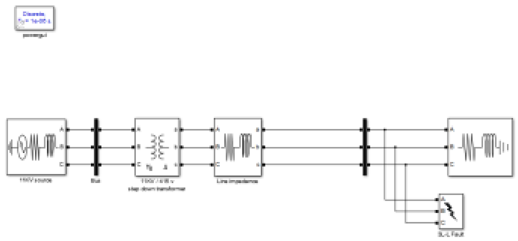

Figure 6. Simulink model of three phase power system network with 3L-L fault

The aforementioned Simulink model is designed for 11kV distribution grid and the 11kV/415V three phase transformer and it is connected with the 415V bus and followed by the linear load. The three phase L-L fault is added with the model ta the load side. The Simulink model after adding the TBSSFCL in series with the feeder line is shown in the following figure 7

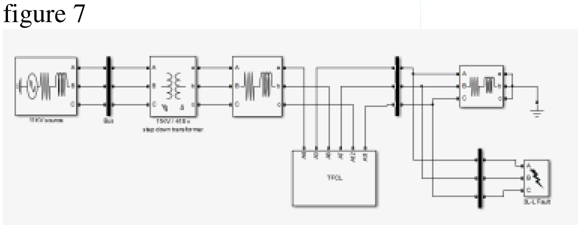

Figure 7 Simulink model of the power system with TBSSFCL

The TBSSFCL is serially added with respect to the feeder line from the main grid. The TBSSFCL is responsible for limiting the over current from due to presence of Fault on the load side. The Simulink model for the TBSSFCL block is represented in the following figure 8.

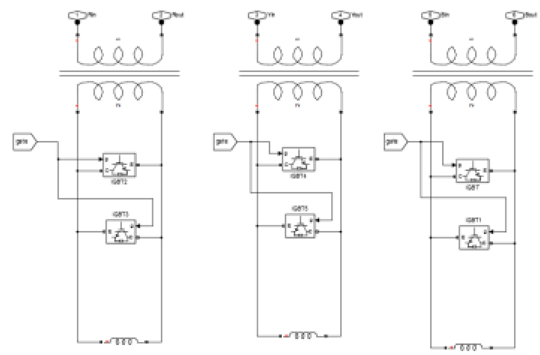

Figure 8 Simulink model for TBSSFCL for single phase line

The IGBTs present inside the TBSSFCL has to be controlled very precisely in order to limit the fault current as dictated at Section III. The main control block for controlling the IGBT is shoen in the figure 9. The circuit contains comparator cirucits and that comparing the actual value of line current with the referencee current and turning off the IGBT by controlling its Gate pulse and parallelly limitinf the high rate of fault current on the system .

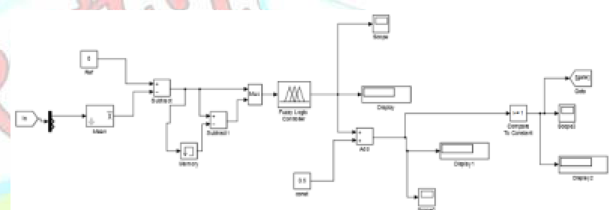

Figure 9. Simulink model for IGBT control block

The Gate pulse generated for the IGBTs in the TBSSFCL is shown in the following figure. The Plot represents that the L-G fault is injected between the time intervals 0.002 to 0.004s. The control block shown on the above figure produces the logic ‘0’ at the fault occurrence time. Hence by the IGBTs are in the OFF state.

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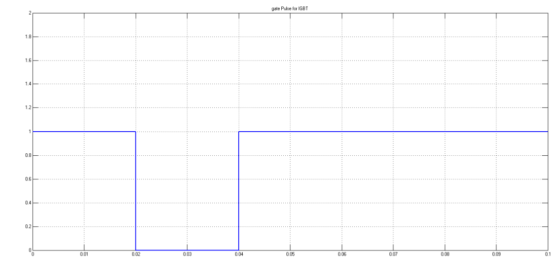

Figure 10.Generated gate Pulse for IGBT

The injected 3L-L fault current and voltage are measured with the help V-I measurement block and the corresponding waveforms are shown in the following figure 11.

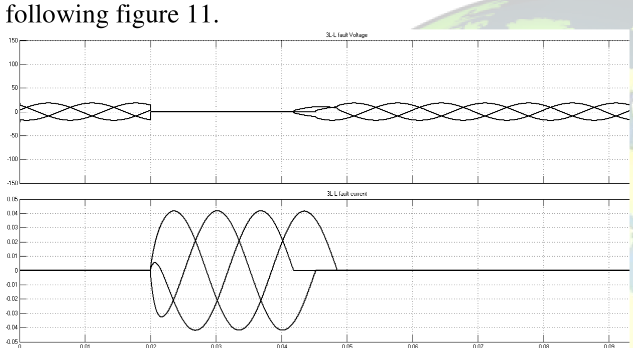

Figure 11. 3L-L fault voltage and current

The fault current limitation is analyzed on both load side and source side and with and without TBSSFCL block. The current waveforms on the source side with fault on two cases ie. with and without TBSSFCL is represents in the following figures 12 and 13 respectively.

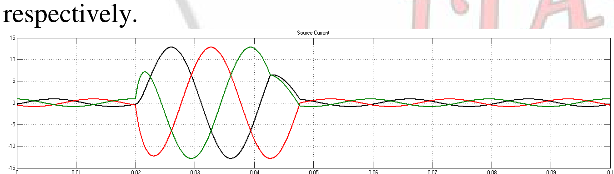

Figure 12 Source side current with Fault & without TBSSFCL

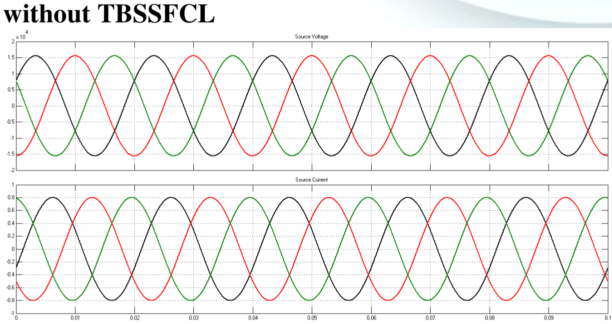

Figure 13. Source side voltage & current with Fault &TBSSFCL block

The above waveforms demonstrates the importance of TBSSFCL on the power system very clearly. The source current and voltage are still stable during the fault occurrence time period [0.002 to 0.004s]. By this way the TBSSFCL supports the source side stability at critical scenarios.

The voltage and current waveforms on the load side with fault on two cases ie. with and without TBSSFCL is represents in the following figures 14 and 15 respectively.

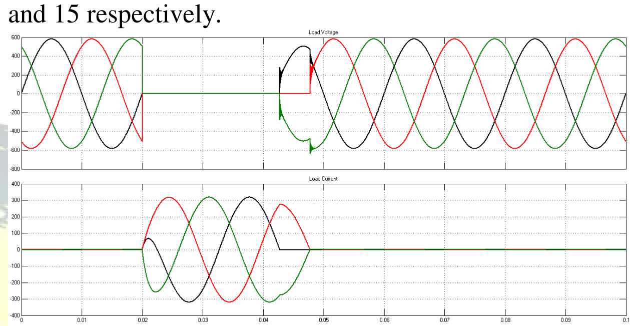

Figure 14. Load Voltage & current with Fault & without TBSSFCL

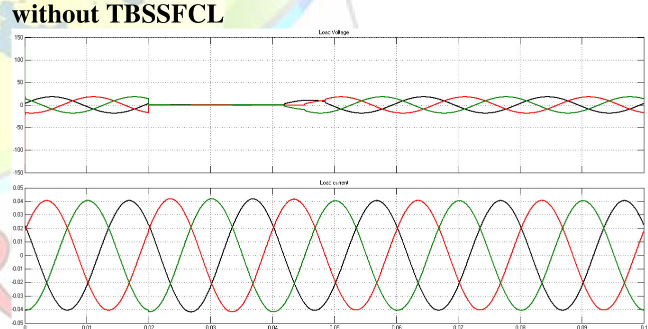

Figure 15. Load voltage & current with Fault &TBSSFCL block

The above waveforms demonstrates the importance of TBSSFCL on the power system very clearly. The source current and voltage are still stable during the fault occurrence time period [0.002 to 0.004s]. By this way the TBSSFCL supports the source side stability at critical scenarios.

V. CONCLUSION

In this work, a novel Fuzzy logic basedFCL configuration, called TBSSFCL, has been proposed for a power system. The work is simulated on MATLAB Simulink platform and the system performance was tested with normal and fault condition such as Line fault and ground fault. The proposed system successfully limiting the fault current at load side. The main advantages of the proposed TBSSFCL are its lower switching

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overvoltage and power loss, compared with other recently suggested SSFCLs, which have high power loss in damping resistor and require cooling system. Omitting the diode bridge rectifier, cooling system and damping resistor results in lower initial cost in the suggested TBSSFCL. Simpler structure also guaranties safe and reliable operation.

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