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Protection of UPQC Against the Load Side Short Circuits

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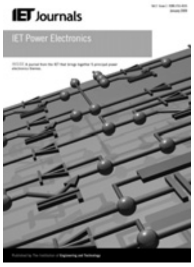

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Protection of unified power quality conditioner against the load side short circuits

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Abstract: This study presents a protection scheme for protecting the series inverter of a unified power quality conditioner (UPQC). The proposed scheme protects the series inverter from overcurrents and overvoltages, which appear during short-circuit faults on the load side of the UPQC. The main protection element is a crowbar connected across the secondary of the series transformer and consists of a pair of antiparallel connected thyristors, which is governed by a simple Zener diode-based control circuit. In the case of an overvoltage, the crowbar short circuits the secondary of the transformer, thus removing the overvoltage and diverting the fault current from the series inverter. An additional circuit is used to disable the inverters in overcurrent conditions. The effectiveness of the proposed protection scheme is demonstrated both through simulation and experimentation.

1 Introduction

The unified power quality conditioner (UPQC) is a custom power device, which is expected to be one of the most powerful solutions for power quality improvement in distribution systems. It integrates series- and shunt-active power filters, combining the operations of these two filters together [1, 2]. Fig. 1 shows a basic system configuration of a general UPQC.

On the DC side, the two filters are connected back-to-back sharing a common DC capacitor. The series component of the UPQC inserts an appropriate voltage to maintain the voltage at the load terminals at a desired level which is balanced and free of distortion (within the limits prescribed by standards). This voltage is derived from a voltage source inverter (VSI) operated under pulse width modulation. Simultaneously, the shunt component of the UPQC injects current in the AC system such that the currents entering the bus to which the UPQC is connected also meet the required standards.

The series converter of the UPQC is connected in series with the electricity supply and this presents an imminent danger to the series VSI when there is excessive current flowing from the supply. Such a situation may arise because of several reasons but primarily as a result of a short circuit on the load side. Before proceeding to explain the operation of the proposed protection scheme, it is worth highlighting the issues involved with a load side short circuit.

The series VSI is typically connected to the grid through a low-pass filter and a coupling transformer (see Fig. 1). When a load side short circuit occurs, the voltage across the load is nearly zero, and almost all the supply voltage becomes proportionally distributed between the series coupling transformer and the impedance of the supply system. Since the supply system impedance is much smaller than the impedance introduced by the series compensator (consisting of the transformer impedance plus the referred impedance of the series low-pass filter), a considerably bigger portion of the supply voltage drops across the primary of the transformer. In the case of a stiff supply, it can be considered that all the supply voltage is applied across the primary of the series coupling transformer. However, usually the rated voltage of the transformer primary winding would not be greater than 50% of the supply nominal voltage, when desired level of compensation is not more than 50% (as higher ratings may not be economically practical [2, p. 350] from power quality disturbance statistics). Thus, during the load side short circuit, the primary of the series coupling transformer

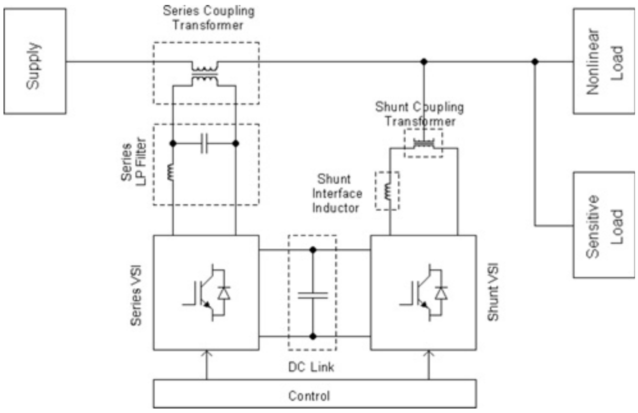

Figure 1 *UPQC structure*

experiences the full referred phase voltage, which is reflected in the secondary side of the transformer and the series VSI. In such circumstances, even if the series VSI is disabled, it acts as a diode rectifier, and the DC capacitor will rapidly charge beyond the voltage ratings of the DC capacitor and the series VSI switches. Thus, the protection circuit should be able to clamp the voltage across the secondary of the series coupling transformer.

The series coupling transformer is connected in series with the feeder and must be operated like a current transformer, which means that a path for current flow on the secondary side must be provided. In normal operation, the series VSI switches provide this path for the secondary current. However, during a short circuit on the load side, the current flowing through the secondary of the series coupling transformer, and hence through the series VSI switches, is considerably above their ratings. Although the series coupling transformer can be designed to withstand the short-circuit current until the fault is cleared by the system protection, the series VSI switches can be destroyed if proper protection measures are not taken, because the short-circuit current can easily exceed the maximum current capacity of the individual insulated gate bipolar transistors (IGBTs). In the event of a fault in a distribution network, the fault is cleared after a duration which is determined by the time delay imposed by the protection system. This delay in turn is determined by the response time of the switching devices and the requirements of the protection co-ordination. As noted in [3, 4], the total clearing time of a low-voltage circuit breaker depends on the amplitude of the fault current, but usually has a minimum time of 45 ms, whereas the minimum clearing time can exceed 100 ms for medium-voltage applications. The switching devices in the series VSI are not rated to carry the fault current for such a long duration. Thus, the VSI switches are the most vulnerable to short circuits on the load side of the UPQC, and special protection has to be designed to protect them from such faults.

The series VSI cannot be protected from the short-circuit currents by simply disabling the VSI gate signals or using circuit breakers or fuses. The response times of circuit breakers and fuses are such that they cannot be used for protection of power electronic devices against overcurrent. Opening the secondary of the series coupling transformer will cause magnetomotive force (mmf) unbalance, which in turn drive the transformer into magnetic saturation, leading to excessive voltage across the secondary winding. Therefore during a short circuit on the load side, a special path must be provided for the flow of the secondary current, which will divert the excessive current from the series VSI switches. The elements forming this path are appropriately rated depending on the level and duration of the fault current.

When the supply system is undergoing a deep voltage sag, the supply voltage may be lower than the rated voltage of the series transformer primary winding. Even during a voltage sag, if a load fault occurs, then the short-circuit current is still much higher than the series VSI rating. In this case the protection circuit must disable the inverter switches, in order to protect the series VSI from overcurrent.

The series VSI protection must not interfere with the protection installed upstream in the distribution network. Such protection systems rely on detection of substantial overcurrent. If this overcurrent is greatly reduced because of the operation of the series VSI protection, the upstream protection in the distribution network may not clear the fault or clear it with an unacceptably long delay. Thus, when designing the series VSI protection, such interference should be excluded.

As a path for the secondary current must be provided, the performance of varistors and a pair of thyristors in parallel with the secondary of the series coupling transformer has been investigated in [3, 4]. The protection scheme proposed in [3, 4] is shown in Fig. 2*a*.

Although the protection schemes proposed in [3, 4] are simple and easy to implement, and have no interference with the power distribution system protection, the use of varistors causes some disadvantages. As mentioned in [3], varistors can initially fail in a short-circuit mode when subjected to surges beyond their peak current/energy ratings. Also, they may fail in a short circuit when operated at steady-state voltages well beyond their ratings values. This mode of stress may result in an eventual open circuit of the device because of the melting of the lead solder joint. When the varistor is in open circuit, the current flowing through it is zero, and the control circuit that generates the gating signals for the thyristors (proposed in [3]) will not generate any signal. If the varistor circuit is open and the thyristor couple is in the off state, large overvoltages will appear across the secondary of the coupling transformer, which will be applied to the series VSI. Another drawback of this protection scheme is failure to protect the series VSI from overcurrent in the situation where the short circuit on the load side occurs when the supply system is simultaneously undergoing a deep voltage sag. In this case, the supply voltage may appear to be lower than the reference voltage at which the varistor

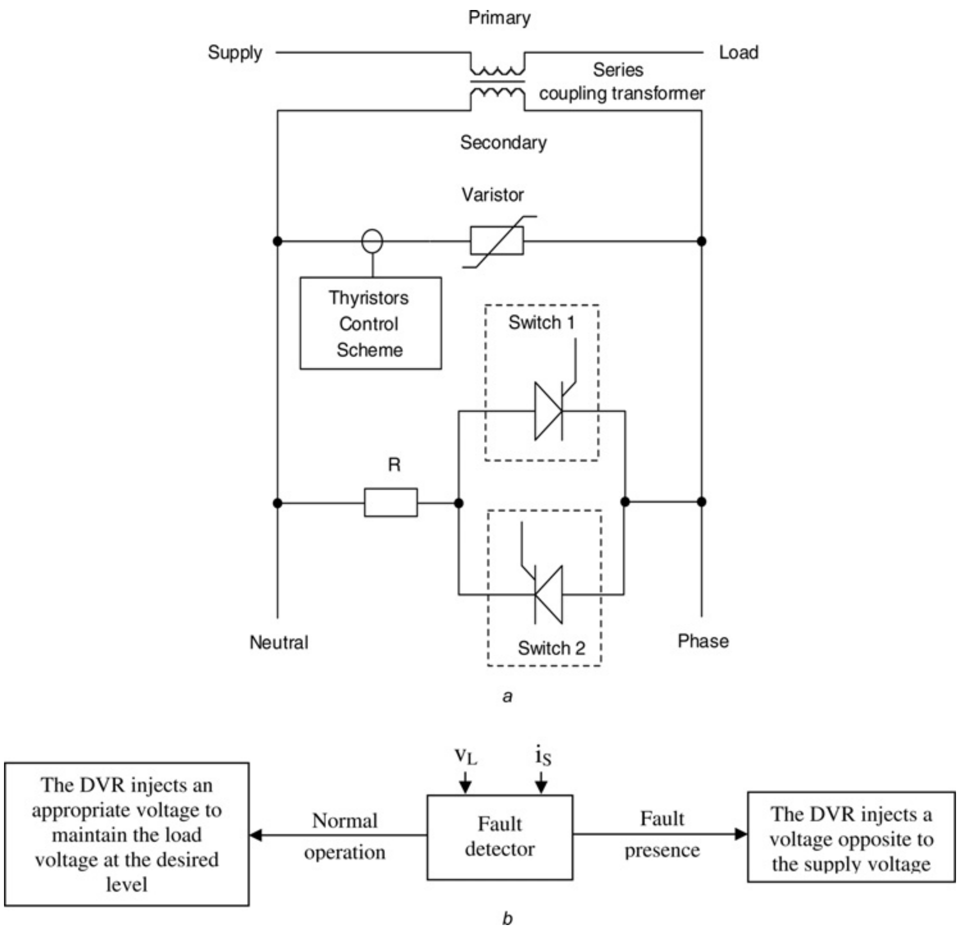

Figure 2 *Protection schemes previously reported in the literature*
a Varistor-based protection scheme
b Control strategy for protection based on additional control function

clamps. Since the varistor does not clamp, the gate signals for thyristors are not generated, and the protection does not divert the short-circuit current from the series VSI, which is not disabled. Although the short-circuit current is reduced in this case because of the voltage sag, the current is still much higher than the series VSI ratings.

A different protection approach is proposed in [5, 6], which involves an additional control function combined with the normal operating scheme of the series compensator. The basis of the scheme is that when an overcurrent occurs in the distribution system, the series compensator reverses its injected voltage polarity so as to minimise the current flow. This control strategy is schematically presented in Fig. 2*b*.

The protection schemes proposed in [5, 6] ensures that the VSI switching devices are protected from excessive high current without additional circuit complexity. However, this protection approach can only be applied when the nominal voltage of the primary winding (connected to the grid) of the series coupling transformer is close to the nominal voltage at the point of common coupling of the UPQC. In other words, this means that the series coupling transformer will have an increased rating which may prove uneconomical [2, p. 350].

In this paper a protection scheme based on a pair of antiparallel connected thyristors is proposed. Because the proposed scheme does not use varistors for clamping the secondary voltage of the series coupling transformer, this solution does not suffer from the drawbacks mentioned above for the solutions proposed in [3, 4]. The thyristors are governed by a simple Zener diode-based control circuit, which does not require a separate power source. The overvoltage across the secondary of the series coupling transformer is detected by this control circuit and clamped by a couple of antiparallel thyristors. The protection scheme proposed in this paper is simple and easy to implement, and it does not interfere with the upstream protection installed in the power distribution system. It serves to protect the series VSI from both overvoltages and overcurrents during load side short circuits.

2 Proposed protection circuit

A protection scheme against the load side short circuits has been derived and implemented in the UPQC laboratory prototype. As mentioned earlier, if a short circuit occurs at the load side of the UPQC, the secondary of the series transformer has to be short circuited in a reasonably short time (microseconds), in order to protect the series inverter from overvoltage and overcurrent. It is proposed to accomplish this short circuiting by using a pair of antiparallel connected thyristors, governed by a simple Zener diode-based control circuit. The proposed protection scheme is shown in Fig. 3.

The proposed protection scheme is a controlled crowbar, which is connected across the secondary of the series transformer and short circuits it when an overvoltage occurs across the transformer secondary. Because a short circuit on the load side of UPQC usually results in an overvoltage across the secondary of the series transformer, the protection operates and the large short-circuit current flowing from the supply side is diverted from the series inverter switches to the thyristors of the protection scheme. The inverter switches are simultaneously protected from both overvoltage and overcurrent during such a fault. The operating principle of the scheme is explained for the positive half cycle of the voltage waveform (thyristor THp is forward biased). From Fig. 3 we can see that the voltage across the thyristors is also the same as the voltage applied to their control circuits. Although the voltage across the thyristor THp is of forward polarity, but not greater than the rated breakdown voltage of the Zener diode ZDp, the latter is not conducting and the voltage across the resistor Rp is of a very low value and is insufficient to turn on the thyristor. Therefore the thyristor remains forward blocked. As soon as the forward polarity voltage across the thyristor is higher than the rated breakdown voltage of the Zener diode ZDp, the latter starts to conduct and the voltage across the resistor Rp increases until it is at a sufficient level to fire the thyristor. The thyristor THp turns on and short circuits the secondary of the transformer. When the current through the thyristor tries to go negative, it turns off. During the negative half-cycle of the voltage waveform thyristor, THn operates on the same principle. The Zener diode breakdown voltage determines the reference voltage (at which the thyristors are triggered into the ON state) of the protection scheme. The diodes Dp and Dn prevent the forward conduction of Zener diodes ZDp and ZDn, respectively.

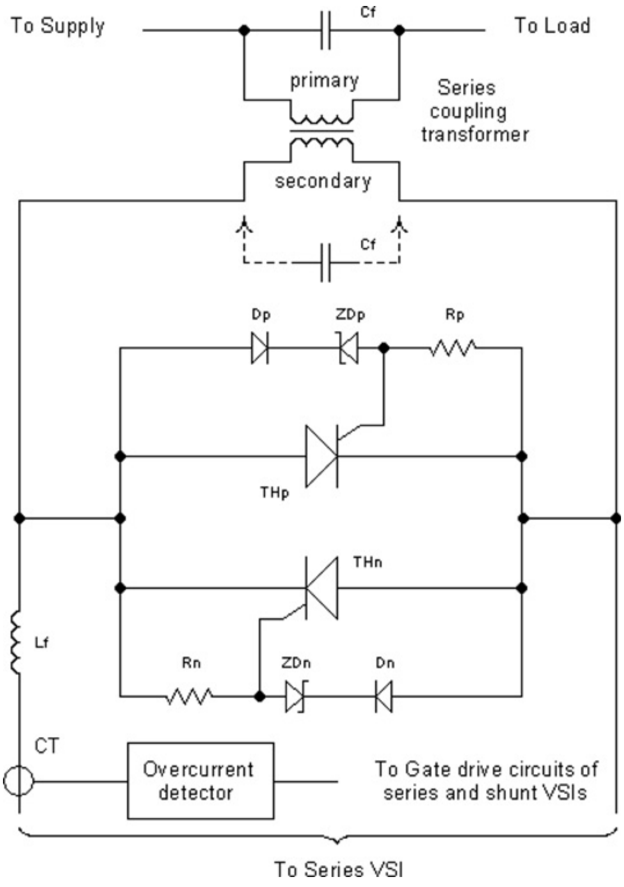

Figure 3 *Thyristor-based series VSI protection scheme*

As mentioned above, the short-circuit current flowing from the supply side is diverted to the thyristors of the protection scheme. However, since the series VSI remains in operation, a large current will flow through it, which comes from the DC side. In order to interrupt the path for this current, the series VSI switches must be disabled. Thus, as soon as the secondary of the series transformer is short-circuited by the protection scheme, the gate signals of the series VSI have to be disabled in a reasonably short time. Also, in order to prevent the short circuit on the load side being fed from the DC link, through the shunt part of UPQC, the gate signals of the shunt inverter also must be disabled. For generating the gate disabling signal a current transformer or transducer is used for measuring the current through the series VSI (see Fig. 3). In the secondary of this current transformer, an overcurrent detector is connected. During the normal operation the currents flowing through the series VSI are below the threshold value and the overcurrent detector generates an output signal, which enables the operation of both the series and the shunt inverter. As soon as a current higher than the threshold value is flowing through the series VSI, the overcurrent detector generates a disabling output signal, which is applied to both series and shunt VSIs gate drive circuits. The faster the overcurrent detector circuit initiates the disabling of the VSIs the better. For smaller threshold currents, the disabling occur more rapidly (see Fig. 4). Thus, for faster disabling of the VSIs, it is preferable to have a threshold current not much higher than the maximum current through the series VSI during normal operation.

The overcurrent detector is constructed such that it continues to generate the disabling signal even after the input signal is greatly reduced or removed. In other words, it memorises the overcurrent occurrence. The necessity of having the memory function is dictated by the fact that as soon as the VSIs are disabled, the currents through them are reduced to almost zero. In the absence of a memory

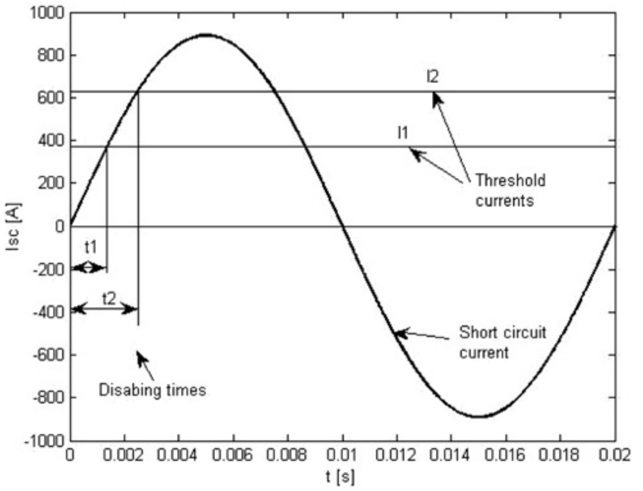

Figure 4 *Dependence between the threshold current and disabling time*

function, the overcurrent detector would intermittently enable and disable the VSIs while the overcurrent condition exists. A specific reset action is required (manual or from a dedicated circuit) to reset the overcurrent detector.

In order to cancel the switching frequency harmonics produced by the series VSI, a low-pass filter is inserted between the series VSI and the series transformer, which consists of an inductor and a capacitor. This filtering capacitor can be either connected across the secondary of the series transformer or across the primary. In Fig. 3, the eventual connection of the filtering capacitor Cf across the secondary of the series transformer is shown by a dashed line. In this case, when the protection scheme short circuits the secondary of the transformer, the capacitor Cf also becomes short circuited. The current through the conducting thyristor is the sum of two components: short-circuit current originating from the supply and the series VSI, and the current because of the discharging of the capacitor Cf. The current component because of the discharging of the capacitor Cf introduces spikes in the overall short-circuit current through the protection crowbar, as shown in the simulation results in Fig. 5*a*. These spikes are periodic (once per half cycle) and put additional stress on thyristors during the discharging of capacitor Cf.

An eventual solution to this problem would be the insertion of an appropriate value resistance in series with Cf or with the protection crowbar. This can reduce the Cf discharging current and change its dynamics such that the spikes disappear. However, this solution requires additional hardware and causes additional losses. Also, if the resistor is connected in series with the protection crowbar, the magnitude of the short-circuit current flowing from the supply can be greatly reduced which can adversely affect the upstream protection. This needs to be evaluated. Another solution is to connect the capacitor Cf across the primary of the transformer (instead of being connected across the secondary), as shown in Fig. 3. In this case, the capacitor Cf is distant from the protection crowbar and during the short circuit the discharge of the capacitor does not create current spikes, as shown by the simulation results in Fig. 5*b*. When the voltage and power rating goes up, the value and the cost of the shifted capacitance, protection co-ordination and so on need to be evaluated before finalising the design.

The protection scheme must not operate in the case of slight transient overvoltages that can appear across the secondary of the series coupling transformer during normal operation of the UPQC. The erroneous tripping of the protection crowbar during normal operation can cause a stability problem. In this case, the UPQC, instead of improving the power quality, will worsen it. In order to prevent this overvoltage protection malfunction, the reference voltage of the protection crowbar has to be set higher than the transient overvoltages which can arise during normal operation. At the same time, the voltage ratings of the series VSI and DC capacitor should be

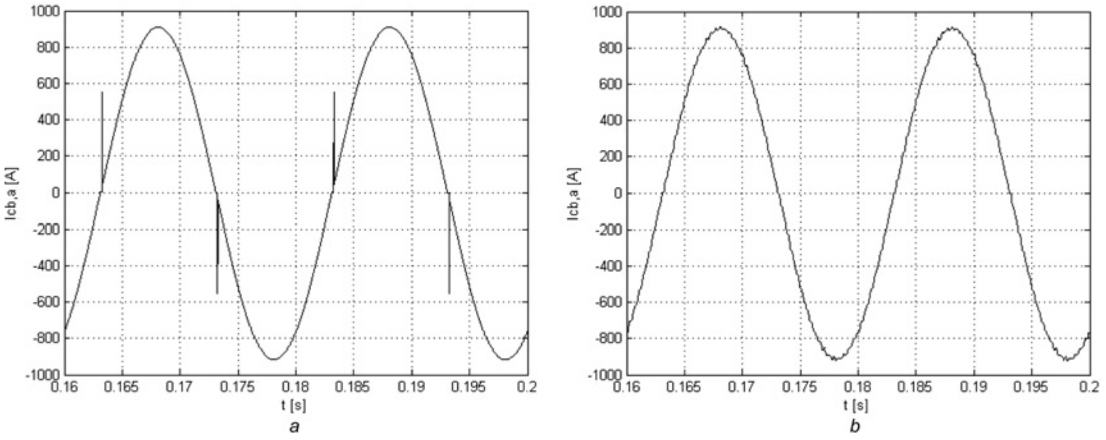

Figure 5 *Current through phase a of the protection crowbar during the short circuit*

a Cf is connected across the secondary of the series transformer
b Cf is connected across the primary of the series transformer

chosen such that these devices can withstand normal operational overvoltages.

3 Simulation results

In order to investigate the performance of the proposed protection scheme, its model was incorporated into a three-phase, three-wire UPQC model, created in Simulink, and the appropriate short-circuit conditions were simulated. The system under investigation is a 400 V three-phase three-wire system with a fault level of approximately 1.2 MVA. A linear AC load of 6 kW and 6 kVAr is supplied. In addition, a non-linear AC load (RL load connected to a rectifier) is supplied, which draws 5 kW. On the DC side a capacitor of 2000 μF is used. The interface inductors of both the shunt and series branches have the following parameters: $L = 1.245$ mH and $R = 0.1\ \Omega$. The filter capacitors used with the series and shunt branches are 140 and 20 μF, respectively. A 4 Ω damping resistor is connected in series with the shunt filter capacitor. Coupling transformers are used to connect the series- and shunt-active filters to the grid. The parameters of these transformers are given in Table 1.

During the normal operation, the series inverter is controlled to compensate for sags/swells in the supply voltage. The shunt inverter is controlled to compensate for the reactive and harmonic components of the load current and to maintain the average voltage across the DC capacitor at the level of 400 V. The shunt inverter is controlled in such a way that the tracked current is kept within the hysteresis band of ± 1 A (4.4% of the load fundamental current), which results in an average switching frequency of 5.8 kHz. The switching frequency of the series inverter is 5 kHz.

The threshold for the overvoltage protection crowbar is set to 300 V. The series VSI is disabled as soon as its current exceeds 100 A. In all cases under investigation a three-phase short circuit on the load side was created at 0.1 s and lasted for 100 ms. For Case Studies 1, 2 and 3, the supply voltage is at the nominal level (230 V line to neutral), and the series compensator does not inject any voltage. In Case Study 4 the supply system is undergoing a 50% voltage sag and therefore, in order to maintain the load voltage at the nominal level, the series compensator is injecting an appropriate voltage.

Table 1 Transformers parameters (series/shunt)

Rating, kVA	4 (per phase)/12	
core resistance, pu	110/117	
core inductance, pu	90/248	
	Primary	Secondary
Voltage, V	115/230	130/130
winding resistance, pu	0.02/0.006	0.02/0.006
winding leakage inductance, pu	0.02/0.002	0.02/0.002

3.1 Case Study 1

In the Case Study 1 there is no protection crowbar across the secondary of the series transformer and during the fault the series VSI is not disabled. Since in this case the secondary of the series transformer is short circuited through the series VSI switches, there is no overvoltage across it during the fault. However, as it can be seen from Fig. 6, the series VSI experiences an overcurrent. During the fault the current through the series VSI switches exceeds 400 A (peak), whereas its maximum rating is 150 A. It is expected that the devices of the series inverter will be damaged or destroyed because of such excess current.

3.2 Case Study 2

In the Case Study 2 there is also no protection crowbar across the secondary of the series transformer, but the series VSI is disabled during the fault. In this case, since the series VSI is disabled the current flowing through it during the fault is reduced to zero. However, an overvoltage appears across the secondary of the series transformer and, as a result, across the DC link. From Fig. 7 we can see that the voltage across the DC capacitor is higher than 650 V. Under the present situation it exceeds the voltage limit of the DC capacitor, which will be damaged because of uncontrolled excess charge accumulation. Also, the maximum rating for the collector–emitter voltage of the series VSI IGBT switches is 600 V. Thus, the simulation results from Case Studies 1 and 2 show that during a short circuit on the load side of UPQC the series VSI is exposed to either an overcurrent or an overvoltage. In order to prevent the device being damaged, a special fast acting protection has to be used.

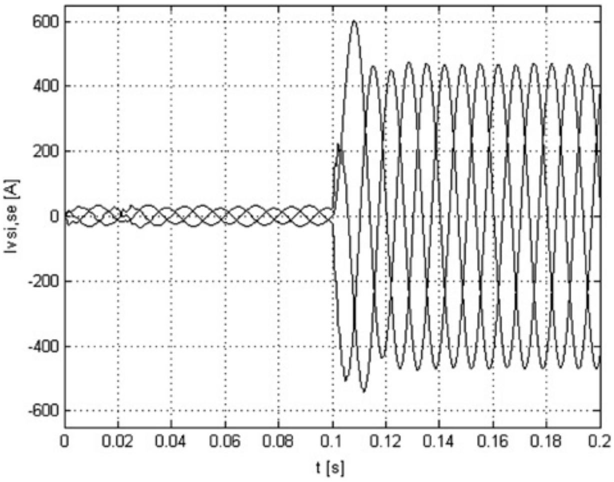

Figure 6 *Currents through the series VSI, Case Study 1*

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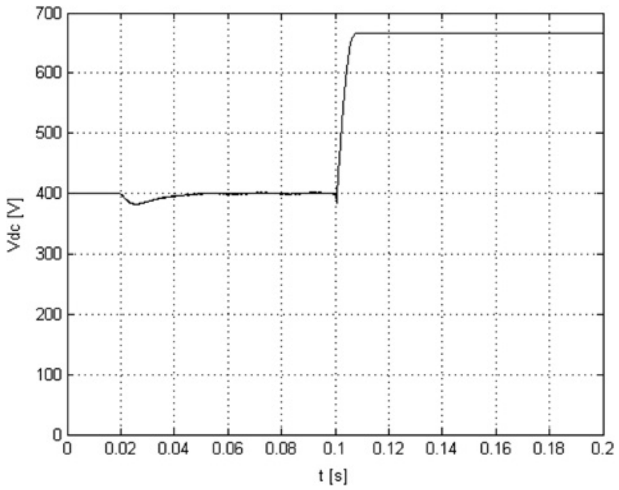

Figure 7 *Voltage across the DC capacitor, Case Study 2*

3.3 Case Study 3

In the Case Studies 3 and 4 the proposed protection is connected and the effects of its operation can be observed on the results presented below. From Fig. 8*a* we can see that, after the fault occurrence (at 0.1 s), as soon as the magnitude of the current through the series VSI increased to 100 A, the protection disabled the inverter switches and the current quickly reduced to zero.

From Fig. 8*b* we can see that because of the operation of the protection crowbar, the voltage across the secondary of the series transformer is clamped to 300 V. As a result, there is no overvoltage across the DC link (see Fig. 8*c*). Thus, during the fault, because of the operation of the protection, the series VSI does not experience either overcurrent or overvoltage.

3.4 Case Study 4

As mentioned above, in the Case Study 4 the supply system is undergoing a 50% voltage sag. The supply voltage in this case is about 115 V (r.m.s.), and during the fault the voltage across the primary of the series transformer does not exceed the rating (115 V). Thus, because of such a deep voltage sag, there is no overvoltage across the secondary of the series transformer during the fault. From Fig. 9*a* we can see that during the fault the steady-state voltage across the secondary of the series transformer is about 180 V peak. Since the secondary voltage is less than the threshold (300 V), the overvoltage protection crowbar does not short circuit the secondary of the transformer, and in such circumstances there is no necessity. The overcurrent through the switches of the series VSI is prevented by disabling them.

Although during the fault there is no overvoltage across the secondary of the series transformer, in a short time after the fault occurrence, the DC link voltage increased to about 480 V (see Fig. 9*b*). This DC link voltage increase is due to the fact that the voltage across the secondary of the transformer does not return to the steady state immediately after the fault occurrence, but goes through a transient

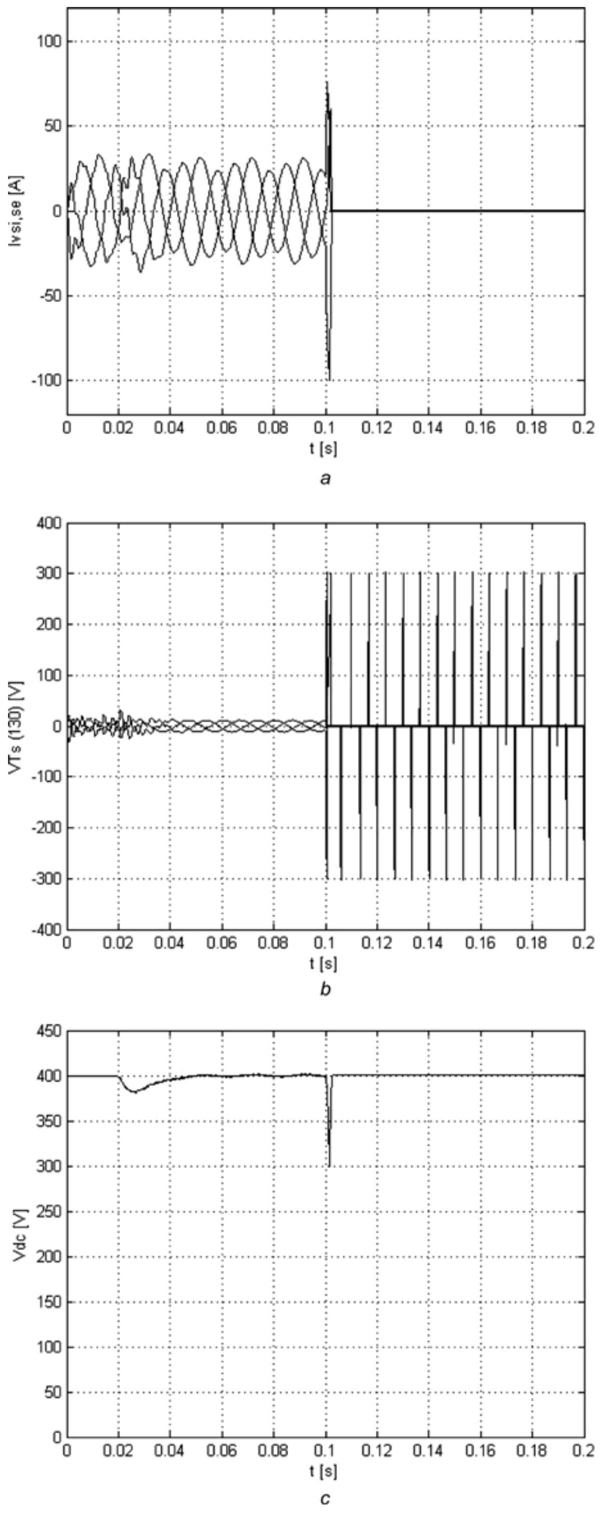

Figure 8 *Simulation results for Case Study 3*

a Currents through the series VSI
b Voltages across the secondary of the series transformers
c Voltage across the DC capacitor

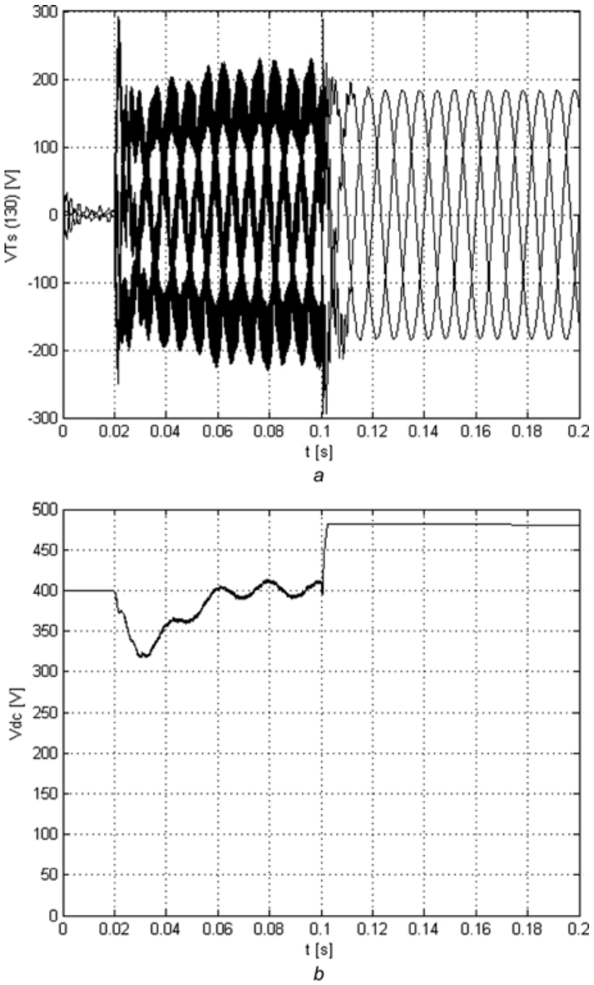

Figure 9 *Simulation results for Case Study 4*

a Voltages across the secondary of the series transformers
b Voltage across the DC capacitor

(see Fig. 9*b*). During this transient, although the voltage across the secondary does not exceed 300 V (the threshold), the line-to-line voltage, which is applied through the series VSI across the DC capacitor, in the worst case can be as high as 600 V. Since after the transient the DC capacitor does not discharge significantly, the voltage across it remains at the level it reached during the transient (see Fig. 9*b*). Therefore the series VSI and DC capacitor ratings have to be chosen accordingly.

4 Experimental results

Based on the investigations presented above, an experimental overvoltage protection circuit has been designed, built, tested and incorporated into a UPQC laboratory prototype. Four Zener diodes (the breakdown voltage of each is 75 V) have been connected in series to set the protection threshold to 300 V. The protection circuit has been tested by applying across it a range of voltage levels, close to the threshold (i.e. below and above). A California Instruments AC Power Source has been used throughout the experiment, providing a quasi-ideal 50 Hz sinusoidal voltage. In order to limit the source current, a 70 Ω power resistor has been connected in series with the protection crowbar. The measurements have been performed using a Tektronix oscilloscope (TPS 2024). Fig. 10 shows the experimental results for four different tests. The top signal is the voltage across the protection crowbar. The middle and bottom signals are the voltages across the resistors Rp and Rn, respectively (see Fig. 3). These are also the gate-cathode voltages of, respectively, positive half-cycle and negative half-cycle thyristors (THp and THn in Fig. 3).

In Test 1, the source voltage has been set to 298 V peak, which is lower than the threshold (300 V). The results corresponding to Test 1 are shown in Fig. 10*a*. As we can see from this figure, the entire source voltage appears across the protection crowbar, and the gate-cathode voltages of thyristors are around zero. As expected, since the voltage across the protection crowbar is lower than the threshold, the thyristors are in the off-state and the crowbar appears as an open circuit.

In Test 2 (see Fig. 10*b*), the source voltage is increased to 314 V peak. The biggest part of this voltage (slightly above 300 V) drops across the protection crowbar and the rest of it drops across that 70 Ω power resistor mentioned above (connected in series with the crowbar for limiting the source current). Since the peak voltage across the protection crowbar is now slightly higher than the threshold, voltage impulses (the magnitude is around 0.6 V) appear across the gate cathode of thyristors (see the middle and bottom signals in Fig. 10*b*), but they are not of sufficient magnitude to trigger the thyristors. Thus, the thyristors are still in the off state.

In Test 3 (see Fig. 10*c*), the source voltage is further increased to 321 V peak. Now, when the voltage across the crowbar is higher than the threshold, the gate-cathode voltage pulses are sufficient to trigger the thyristors into the on state. At about 4.3 ms, the voltage applied across the crowbar becomes higher than the threshold and the thyristors are triggered into the on state. Thus, after 4.3 ms, the protection crowbar appears as a short circuit and the voltage across it is almost zero. From Fig. 10c we can see that the voltage across the protection crowbar is clamped to about ±300 V.

In Test 4 (see Fig. 10*d*), the source voltage is 354 V peak. Now, since the source voltage is greater than in Test 3, the voltage across the crowbar exceeds the threshold more rapidly. From Fig. 10*d* we can see that the thyristors are triggered into the on state at about 3.2 ms (in Test 3 it happened at 4.3 ms). As in Test 3, the voltage across the protection crowbar is clamped to about ±300 V.

Thus, from the above tests, it can be concluded that the protection crowbar successfully limits the voltage across it. Voltages below the threshold (300 V) appear across the

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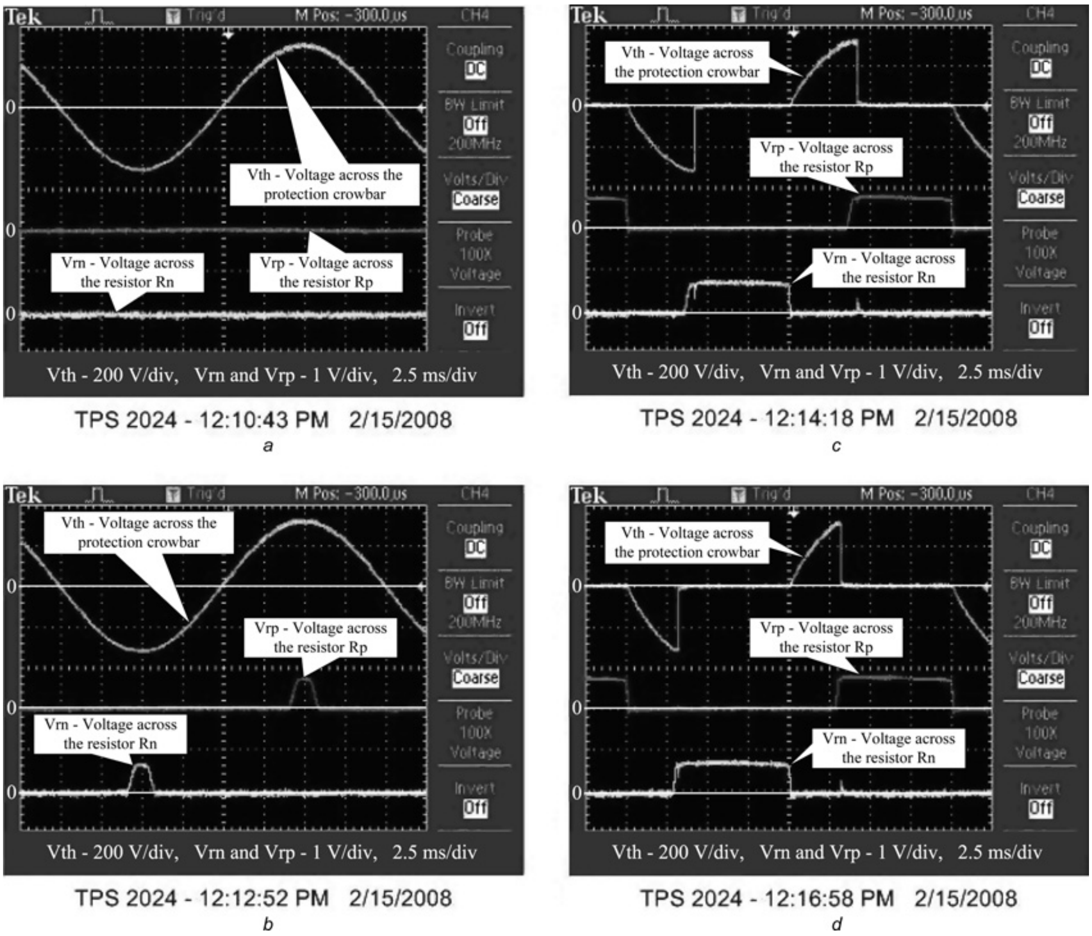

Figure 10 *Experimental results*

a Test 1, $V_s = 211$ V (298 V peak)
b Test 2, $V_s = 222$ V (314 V peak)
c Test 3, $V_s = 227$ V (321 V peak)
d Test 4, $V_s = 250$ V (354 V peak)

crowbar without any change. In the case of overvoltage, the voltage across the protection crowbar is limited to a value slightly higher than 300 V. The thyristors are triggered into the on state after overvoltage occurrence, thus putting the voltage across the protection crowbar to zero.

5 Summary and conclusion

In this paper a protection scheme for the UPQC series inverter has been presented and analysed. The proposed scheme protects the series inverter from overcurrents and overvoltages, which appear during a short circuit on the load side of the UPQC. The main protection element is a crowbar, which is connected across the secondary of the series transformer. As soon as an overvoltage appears the crowbar short circuits the secondary of the transformer, thus removing the overvoltage and diverting the fault current from the series inverter. The overvoltage protection crowbar consists of a pair of antiparallel connected thyristors governed by a simple Zener diode-based control circuit, which does not require a separate power source. In addition, an overcurrent detector is used to disable the inverters in overcurrent conditions. The paper has presented the application of a protection scheme to a series compensator of a UPQC operating at relatively low voltage and current values. The paper has also identified a number of design variations that could be considered when applying this scheme at a higher voltage rating. Detailed design at higher voltage levels would take account of cost, protection coordination and performance consideration.

The effectiveness of the proposed protection scheme has been confirmed through simulations for different fault and system conditions. It has been shown that using the proposed protection scheme the series inverter is fully protected from both overcurrent and overvoltage, and the overall reliability of the equipment is enhanced. Also, an experimental overvoltage protection circuit has been designed, built, tested and incorporated into the UPQC laboratory prototype. The experimental results demonstrate the effectiveness of the proposed protection scheme.

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