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A Technique for Thermal Overload Mitigation in a Self-Healing Intentional Island System Using Only Local Measurements

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Abstract—**Self-Healing Power Systems (SHePS) have potential to greatly improve the resiliency of the electrical grid. Many SHePS concepts rely on high-speed networked communications, which increase costs and can limit self-assembly capability. Thus, SHePS concepts that rely only on local measurements can play an important role. One key challenge in self-assembling systems using only local measurements is in detecting and mitigating thermal overload of conductors. This paper proposes a thermal overload detection and mitigation technique, referred to as the "tapping" method, that utilizes only local measurements. This technique involves patterned switching of line relays to modulate the voltage, and recognition of that switching pattern by downstream load-control relays, which then disconnect minimum-priority loads to relieve the overload. The loads can be automatically reconnected after a set of criteria is met, again using only local measurements. The technique is described in detail and demonstrated in PSCAD simulation.**

Index Terms—**Self-Healing Power Systems; Self-Assembling Power Systems; Thermal Overload Mitigation**

I. Introduction

Self-Healing Power Systems (SHePS) have the ability to automatically restore themselves to a nominal operating state following a major disruption to the system [1]. SHePS improve power grid resilience as they mitigate the impacts of damage and offer shorter recovery times [2-5]. Many SHePS concepts rely on high-speed networked communications [6], which are costly and potentially unreliable during disruptive events [7]. Such SHePS also generally lack the scalability and flexibility to support self-assembly or formation of ad-hoc networked microgrids, which can limit resilience benefits. SHePS concepts that rely only on local measurements and that work with inverter-based sources [8] are a desirable alternative if their performance can be made sufficiently high.

Because of their topological variability, one challenge that arises in SHePS is the detection and mitigation of thermal overloads. The fundamental problem is that line relays can detect when thermal overloads occur, but load control is required to alleviate the thermal overload, and the load-control relays cannot detect thermal overloads on conductors upstream from them. Various forms of artificial intelligence have been applied to this problem [9-11], but the large training data sets required are not available for self-assembling SHePS, particularly those relying only on local measurements.

The contribution made in this paper is a proposed voltage modulation technique to enable a SHePS using only local measurements to alleviate thermal overloads. In this technique, referred to as the "tapping" method, a line relay that senses an overload is opened and closed in a series of "taps" to modulate the voltage downstream from the relay. The load-control relays in that downstream zone can detect this voltage modulation and appropriately relieve the thermal overload by switching off some loads, least-critical loads first. Methods for enabling shed loads to determine when to reconnect to the system are then presented. This paper describes the method and demonstrates it via PSCAD modeling and simulation.

II. Theory

A. Overload detection and mitigation

Consider the example system shown in Fig. 1, which is based on the IEEE 13-bus test circuit [12]. This system is separated into three microgrids by the Microgrid Boundary Relays (MBRs) shown in the figure. Each microgrid has a grid-forming inverter-based resource (IBR) indicated by the green labels at the left of the figure. Line (sectionalizing) relays are shown as red boxes, and load-control relays are shown as yellow boxes.

Consider an example case in which the system in Figure 1 is in the off-grid mode operating only from its inverter-based sources, and a thermal overload of the conductor between

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single-phase line relay R4 (near the center of Fig. 1) and node 684 (to the left of line relay R4 in Fig. 1) occurs. The overload is caused by there being too much load at nodes 611 and 652. Line relay R4, from its local current measurements, can detect that this conductor is loaded beyond its ampacity, but by itself the only action R4 could take would be to open and black out the entire system downstream from R4. It would be more desirable to somehow cause noncritical loads at nodes 611 and 652 to disconnect. Thus, in the method proposed here, the line relay opens and closes ("taps") in a predetermined pattern, which modulates the voltage downstream from the line relay, analogous to sending Morse code along the conductor. Downstream load relays are programmed to look for this pattern, and if it is detected, lower-priority loads are disconnected to relieve the overload.

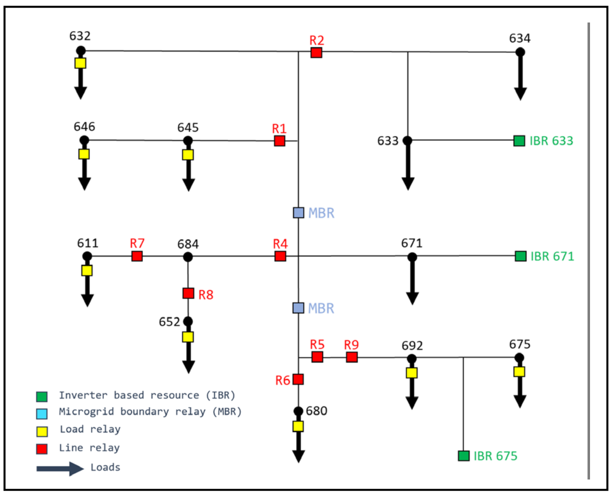

Figure 1. Single-line diagram of the modified IEEE 13-bus test circuit diagram used to describe and test the tapping method.

B. Reclosing Load Relays

After a load relay opens to relieve an overload, it is desirable that the load relay be able to automatically detect when the loading on the line has been reduced to the point at which the disconnected load might be allowed to reconnect. To enable this, the load relays monitor their windowed-average voltage and are allowed to reclose if at least one of three following conditions are met:

- The voltage drops to zero. In this case, the system may have reconfigured and the load may not be served through the same path as before, so the thermal overload issue may no longer exist and the load could attempt to come back online.
- The voltage increases by at least two percent from its previous value. This suggests that another load in the system switched off, freeing enough thermal capacity to reconnect the load that was disconnected to relieve the thermal overload.
- The voltage exceeds 1.0 volts per unit for a preset length of time. This also suggests a load reduction that might have freed up sufficient capacity to allow the disconnected load to reconnect without creating an overload.

If closure of the load relays causes another overload, the tapping of the line relay begins again.

III. Demonstration Procedure

A. Test System

The proposed tapping technique is demonstrated using a PSCAD model of the IEEE 13-bus system. The circuit model is built in PSCAD from the IEEE specification for this system [12]. The model is separated into three microgrids, as shown in Fig. 1. The system is operating in the off-grid mode. Each microgrid is energized by a grid-forming inverter, modeled here using a switching (non-averaged) three-phase H-bridge inverter with forward- and backward-rotating dq0-frame grid-forming controls, with current limiting.

B. Overload Detection and Tapping Implementation

The thermal-overload current thresholds in each line relay were set to 125% of the corresponding cable ampacity. Once a thermal overload is detected, the line relay triggers its tapping sequence. The cable between line relay R4 and node 684 in Fig. 1 has an ampacity of 120 amps, so if the current through R4 exceeds 150 amps, R4 detects a thermal overload of that conductor.

Fig. 2 shows the tapping pattern used by R4 for this demonstration. At roughly t = 3 s, R4 begins its tapping sequence. R4 opens, stays open for 25 milliseconds (selected to be shorter than the zero-voltage duration allowed by the ITIC/CBEMA curves, to avoid adverse impacts on loads), and then recloses. This is one tap. The breaker remains closed for approximately 225 milliseconds before executing another tap. The entire tapping pattern of R4 lasts less than 0.5 seconds and contains three evenly spaced taps. In practice, the duration and spacing of the taps must be chosen strategically. This will be elaborated on in a later section.

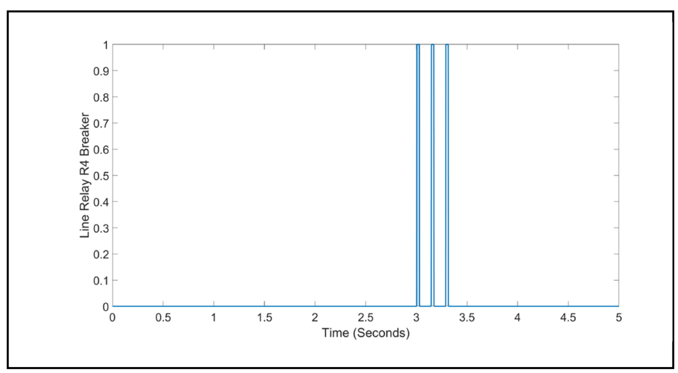

Fig. 2. The tapping pattern used in relay R4 in this demonstration. Accoding to PSCAD's logic, zero indicates a closed breaker and one indicates an open breaker.

C. Detection of the Tapping Signal by Load Relays

Load relays detect and interpret the tapping signal using a finite-state machine (FSM), the flow diagram of which is shown in Fig. 3. The load relay counts one tap if the voltage drops below a pre-determined threshold and recovers within a specified duration. The voltage threshold and the recovery duration are determined by the nature of the expected tapping signal. For instance, load relay 611 in the example counts a tap when the voltage drops below 0.3 volts per unit and recovers within 50 milliseconds.

Each time a tap is detected, the load relay FSM moves to the next state. It will reset if the duration between taps is longer or shorter than a predetermined value. When the highest state is reached, this means that a complete tapping signal was detected, indicating that a thermal overload on a conductor is being sensed by an upstream line relay. The load relay then opens to relieve the overload. It remains open until a separate set of logic determines that it may be safe for the load to come back online, resets the FSM, and closes the load relay. Fig. 3 illustrates this process with an FSM diagram for a load relay that expects a signal to contain four taps.

In Fig. 3, *State 0* transitions to *state 1* when a tap is detected. To ensure the correct signal is detected, *state N* (for $N = 1, 2, 3$) transitions to *state N+1* when a tap is detected within $T_N \pm 10\ ms$, where T_N is the expected time between taps. At state 4, the load relay is opened. It remains open until a reset signal indicates that it may be safe for the load to come back online without causing an overload.

In this example, the FSM interprets three taps as a complete tapping signal and will open load relay 611 immediately after sensing the signal. Load relay 652 will also experience the voltage drops from the tapping of R4. However, in this demonstration, the load at node 611 is designated less critical than that at 652. Thus, when the first "tapping" pattern occurs, load relay 652 will not open. If the first set of "taps" relieves the overload, no more tapping will occur as the issue is resolved. If this does not relieve the overload, line relay R4 will continue to sense an overload and will send another series of taps. This signals line relay 652 to open as well. If after a set number of attempts the thermal overload is not alleviated, then the line relay R4 will open.

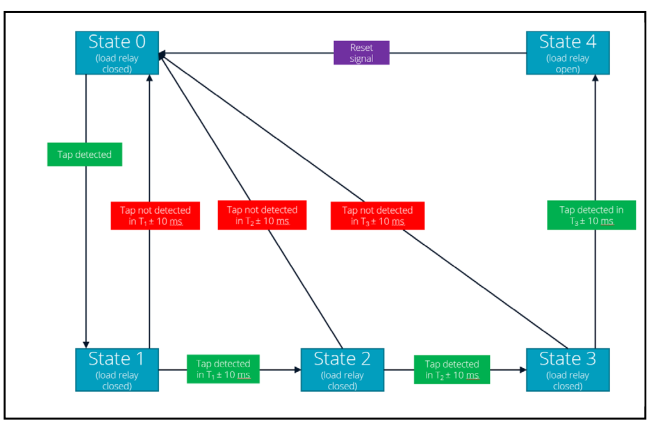

Fig. 3. State diagram of the logic used in the load relays to detect tapping signals.

D. *Reclosure conditions*

In this demonstration, a load control relay is allowed to reclose if its voltage rises above 1.0 pu for 3 seconds.

IV. Demonstration Results

Fig. 4 shows a PSCAD demonstration of a thermal overload event. The top trace in Fig. 3 is the current through line relay R4. At first the current is well below the cable's ampacity, but at t = 1 s excessive load is added and the cable's ampacity is exceeded.

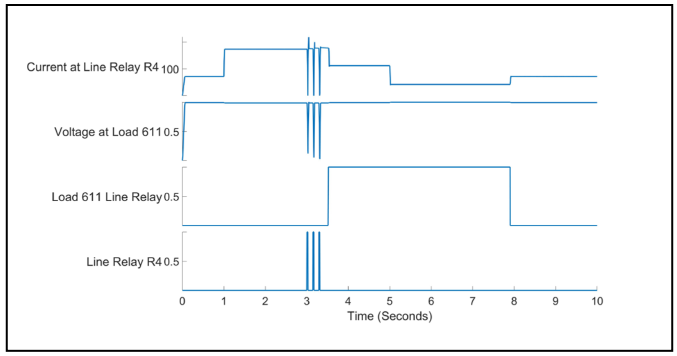

Fig. 4. Current through line relay R4 (top), voltage at load control relay 611 (second from top), load-control relay 611 status (third from top); and status of line relay R5 (botom).

After 2 s of this current, the line relay executes a "tapping" sequence. The bottom trace in Fig. 4 shows the line relay status (0 = closed, 1 = open), and the tapping pattern shown in Fig. 3 is evident at t = 3 s in that bottom trace. The second trace in Fig. 4 shows the voltage at the load control relay for load 611. When the line relay "taps", the load relay sees dips in the voltage, and the FSM at load control relay 611 receives and interprets this signal. Accordingly, immediately after the third "tap", load control relay 611 disconnects its noncritical load, as seen in the third trace in Fig. 4 which is the status of the load 611 breaker (0 = closed, 1 = open). In this case, removal of that load was sufficient to relieve the thermal overload.

Then, at t = 5 s, another load elsewhere on the conductor disconnects. This results in a drop in the current through line relay R4 at t = 5 s (top trace in Fig. 4), and a small change in voltage at load control relay 611, which is difficult to see in Fig. 2 so a zoomed-in view is provided in Fig. 5. The voltage exceeds 1.0, which is one of the conditions that would allow load 611 to reconnect. After the voltage has remained above 1.0 for three seconds, load control relay 611 reconnects, as shown in Fig. 4 (third trace). No thermal overload results, and the system continues to operate.

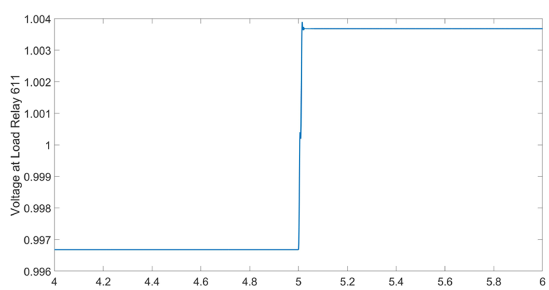

Fig. 5. Voltage at load control relay 611 zoomed in on t = 5 s.

V. Discussion

A. Impact on Breaker Lifetime

Perhaps the biggest potential drawback to the proposed tapping method is its potential adverse impact on breaker lifetimes. Conventional electromechanical medium-voltage distribution circuit breakers can be operated somewhere on the order of 5000 times under full load, depending on several factors [13]. Tapping a breaker in this way will increase the number of operations of the breakers associated with the line relays, which will shorten their lifetimes. It is not yet clear how much their lifetimes would be shortened by this tapping method. Further investigation of this factor is needed. The tapping technique would be more suitable for use with solid-state circuit breakers, which are capable of orders of magnitude more operations [14].

B. Impact of Motor Load on Tapping Signal

Some power system elements, such as motor loads, inline transformers, and shunt capacitors, might have a filtering or smoothing effect on the voltage dips arising from tapping of the breaker. If this effect is too large, it might cause load relays to fail to detect the signal. Figs. 6 and 7 show results from a PSCAD simulation using the 13-bus system with a large three-phase motor load included at load 680 (bottom of Fig. 1). The line relay that is tapping in this case is R6. When excessive load is applied downstream of R6 and it applies the three-tap pattern shown in Fig. 3, Fig. 6 shows that the first voltage dip at load 680's load-control relay is much shallower than was the case with a constant-impedance load, indicating that the motor load has had some smoothing effect on the tapping signal.

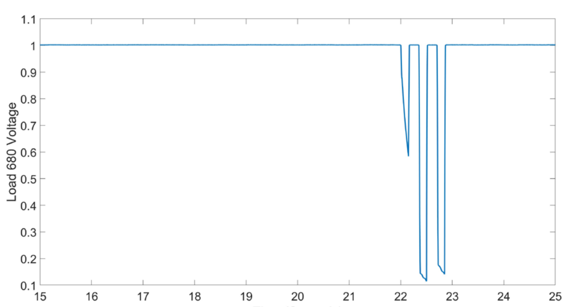

Fig. 6. Voltage at load 680 during "tapping" of R6, with motor load.

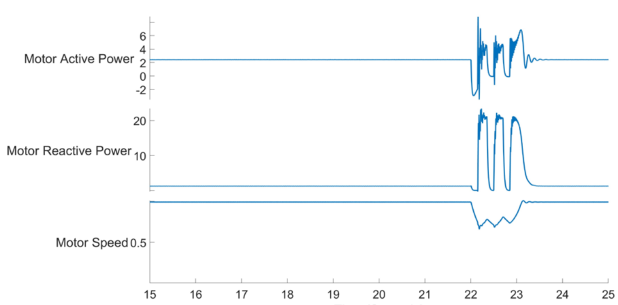

Fig. 7. Motor active power (top), reactive power (middle), and speed (bottom) during application of the three-tap pattern.

Fig. 7 shows the active power (top), reactive power (middle), and speed (bottom) of the three-phase motor during application of the three-tap pattern from R6. The motor's active power does briefly swing negative during the taps, indicating that the motor has briefly entered generator mode and is supplying energy from its rotating mass (as indicated by the changes in speed, bottom trace of Fig. 7). Immediately following each tap, when the voltage returns to nominal, the motor exhibits a reactive current surge, akin to but smaller than a motor-start surge. Fig. 8 shows the induction machine phase currents during this same event.

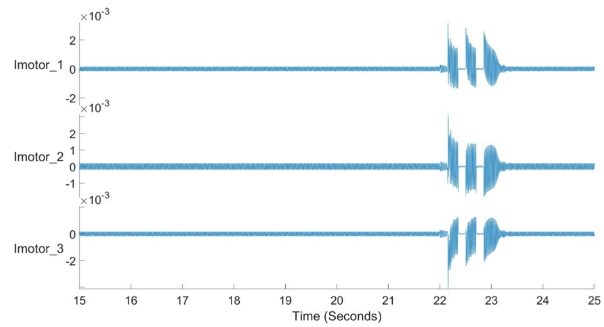

Fig. 8. Phase currents drawn by the three-phase induction motor during the application of the three-tap pattern.

C. Selecting the Tapping Pattern

In addition to the above-described filtering effect, there is a maximum speed at which an electromechanical circuit breaker in the line relay can go from closed to open to closed again, and this will set a limit on the minimum duration of a tap. While many breakers are capable of 25 millisecond taps, this tap duration may be too short for some breakers.

The duration of each tap also cannot be too long. The repeated voltage drops caused by line relay taps are used to send a signal to downstream load relays, but they can also disrupt load function. The tapping pattern shown as an example here was designed so as to not violate the Information Technology Industry Council (ITIC) curve. Simply put, tap durations cannot exceed a length that causes the load voltage to drop too low for too long, or load malfunctions may result.

To avoid nuisance tripping, the tapping pattern must be chosen so that it is minimally likely to be replicated under normal conditions by other system elements.

D. Load Rejection Overvoltage Considerations

If there is little load between a line relay and a source, tapping of that line relay can result in load-rejection overvoltage. For example, in Fig. 1, line relay R9 is the closest line relay to inverter 675. Fig. 9 shows the voltage on the source side of load relay 675 that results from the tapping of line relay R9. Each time R9 is tapped, there is a transient overvoltage reaching a peak of approximately 1.08 p.u. These particular load rejection overvoltages are sufficiently small in magnitude and duration that they do not lead to violations of the ITIC curve, but they are still undesirable.

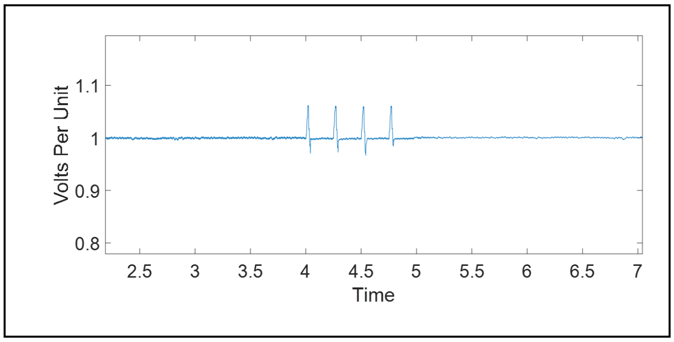

Fig. 9. Voltage measured at line relay R9 during tapping, showing brief load rejection overvoltage spikes.

The practical importance of this issue is debatable, because for a SHePS, planning considerations would result in conductors close to sources being sized to carry the entire output of that nearby source. As a result, thermal overload of these conductors would result in an overload of the source itself. For grid-forming inverters, this would lead to a loss of voltage-regulation capability and an undervoltage, which will trigger other protection systems.

VI. Conclusions

This paper has presented a proposed method for allowing SHePS utilizing only local measurements to detect and mitigate thermal overloads on conductors. This method involves opening and closing a line relay in a specific pattern, modulating the voltage to send a signal to load control relays downstream from that line relay and the thermal overload. Intelligence built into load control relays receives the modulated voltage signal and disconnects the lowest-priority load to alleviate the overload. This process can be repeated if needed, and if several repetitions still do not alleviate the overload, the line relay will open. The paper also presents a set of criteria under which a load relay that was disconnected to alleviate a thermal overload can reconnect, again using only local measurements.

Simulation and testing in PSCAD using the IEEE 13-bus model demonstrated that the tapping method can effectively detect and mitigate thermal overloads using only local measurements. Potential challenges of the tapping method were also identified and discussed.

Future work will include implementing and testing the tapping method in larger and more complex models; investigating the impact on breaker lifetime and identifying breaker types that are most compatible with this technique; and further investigating the impacts on various types of loads.

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