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

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McKendree Densel
Michael E. Ropp
Sandia National Laboratories
Albuquerque, NM USA
meropp@sandia.gov

Elijah Silva
Olga Lavrova
Department of Electrical and Computer Engineering
New Mexico State University
Las Cruces, NM USA

***Abstract*—Self-Healing Power Systems (SHePS) have potential to greatly improve electric power system resiliency. 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 SHePS using only local measurements is in detecting and mitigating thermal overloads of conductors without shedding all loads on the overloaded conductor. This paper proposes a new thermal overload mitigation technique, referred to as the "tapping" method, that 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 system resilience by mitigating the impacts of damage and shortening 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 that utilize local measurements only is the detection and mitigation of thermal overloads. Line relays can detect thermal overloads by comparing their local measurements to the pre-programmed ampacities of the cables on either side of the load relay, but once an overload is detected, the only action a line relay can take is to open and black out the entire system downstream from that line relay. Local load relays could perform much more granular load shedding and alleviate the overload while preserving higher-priority loads, but in local-measurement-only SHePS, the load relays do not have access to the information that a conductor upstream from them is overloaded. Various forms of artificial intelligence have been applied to this problem [9-11], but the training data sets required are not available for self-assembling SHePS relying on local measurements.

This paper proposes a method to achieve more granular load shedding in SHePS, without requiring large training data sets. In this method, a line relay that senses an overload is opened and closed in a series of "taps" to modulate the voltage downstream from that relay. The load-control relays in that downstream zone detect this voltage modulation and switch off lower-priority loads until the overload is mitigated. This paper describes the method and demonstrates it via PSCAD modeling and simulation. Methods for enabling loads to automatically determine when to reconnect are also presented.

## 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.

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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 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 is measuring its local currents, and the ampacities of the cables connected to it are programmed into it in the planning phase. Thus, R4 can determine from its local current measurements that this conductor is loaded beyond its ampacity, but the only action R4 could take by itself 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.

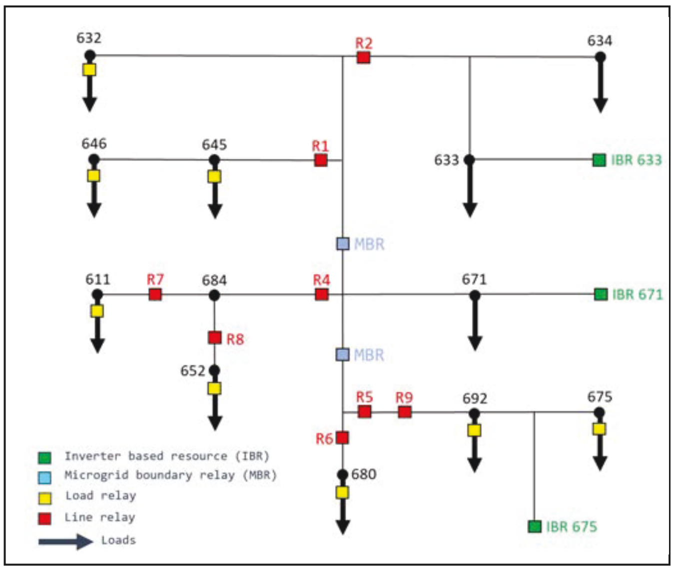


Fig. 1. Single-line diagram of the modified IEEE 13-bus test circuit diagram used to describe and test the tapping method.

### B. *Automatic Reconnection of Shed Load*

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, again using only local measurements. To enable this, the load relays monitor their windowed-average voltage and are allowed to reclose if at least one of three conditions are met:

- The voltage drops to zero, then recovers. This pattern suggests that the system may have been 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 pattern suggests that another load elsewhere in the system has switched off, potentially freeing enough thermal capacity to reconnect the load that was disconnected to relieve the thermal overload.
- The voltage exceeds 1.0 pu 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 and load-shedding cycle is repeated.

## 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 ms (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 225 ms before executing another tap. The entire tapping pattern of R4 lasts less than 0.5 s and contains three evenly spaced taps. In practice, the duration and spacing of the taps must be chosen strategically, as discussed in more detail below.

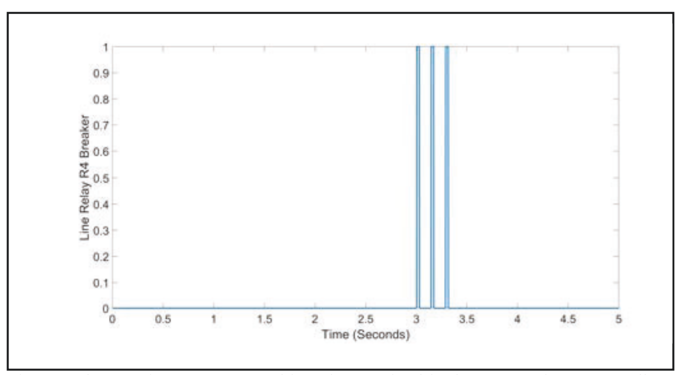


Fig. 2. The tapping pattern used in relay R4 in this demonstration. Accoding to PSCAD's logic, zero indicates a closed breaker and one indicates an open breaker.

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### 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. In this example case, load relays 611 and 652 count a tap when the voltage drops below 0.3 pu and recovers within 50 ms.

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 the 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, and the load relay then opens to relieve the overload. It remains open until a separate set of logic determines that one of the three reclosure conditions described above has been met, at which point it resets the FSM and closes the load relay.

Fig. 3 illustrates this process. *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 $t_N$ ms, where $t_N$ is the time between taps (in this example, all of the $t_N$ values are equal and designated $t_1$). At *state 3*, the load relay is opened, and it remains open until one of the three reset conditions is met. Load relays 611 and 652 both experience the voltage drops from the tapping of R4, but in this demonstration, the load at node 652 is designated higher-priority than that at 611, so when the first "tapping" pattern occurs, load relay 652 will not open; it waits for a second one. If the first set of "taps" relieves the overload, no more tapping will occur. If the overload persists, line relay R4 will send another series of "taps", and line relay 652 will open as well. If after a set number of attempts the thermal overload is not alleviated, then line relay R4 will open.

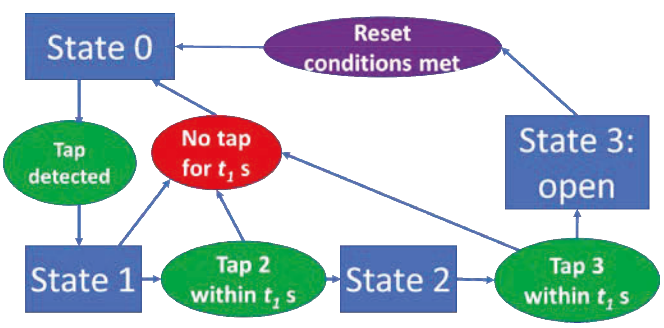


Fig. 3. State diagram of the logic used in the load relays to detect tapping signals.

### D. *Reclosure conditions*

In the work reported here, only one of the three reclosure conditions was tested: a load relay is allowed to reclose if its local voltage rises above 1.0 pu for 3 s.

## 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, load is added and the cable's ampacity is exceeded. 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.

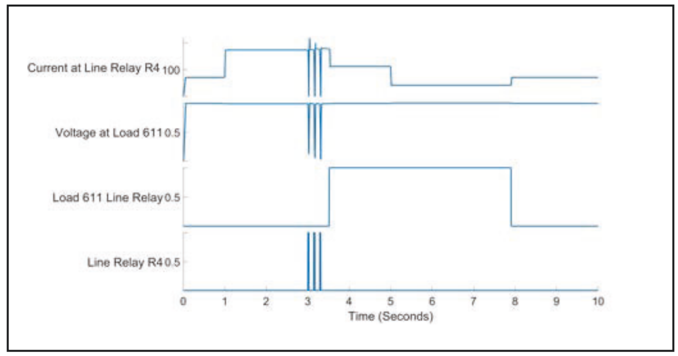


Fig. 4. Current through line relay R4 (top), voltage at load control relay 611 (second from top), load-control relay 611 status (third from top); and status of line relay R5 (botom).

At t = 5 s, another load elsewhere on the system disconnects, resulting in a drop in the current through line relay R4 (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 s, load control relay 611 reconnects, as shown in Fig. 4 (third trace). No thermal overload results, and the system continues to operate.

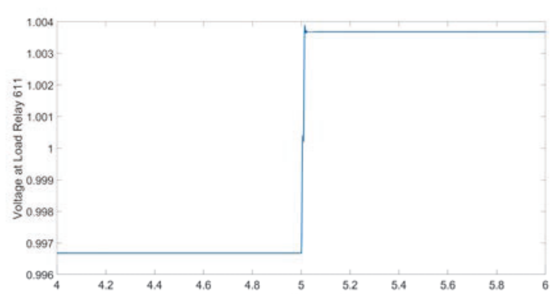


Fig. 5. Voltage at load control relay 611 zoomed in on t = 5 s.

## 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 and shorten their lifetimes. It is not yet clear how large this impact on lifetime would be, and 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.

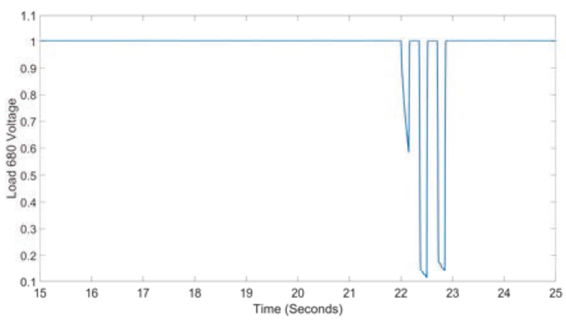


Fig. 6. Voltage at load 680 during "tapping" of R6, with motor load.

Fig. 7 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, and Fig. 8 shows the induction machine phase currents during the same event. .

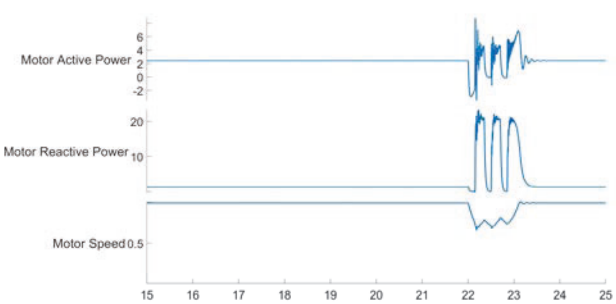


Fig. 7. Motor active power (top), reactive power (middle), and speed (bottom) during application of the three-tap pattern.

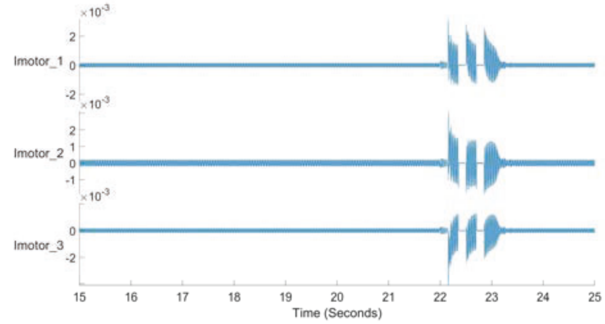


Fig. 8. Phase currents drawn by the three-phase induction motor during the application of the three-tap pattern.

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

## *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 ms taps, this tap duration may be too short for some breakers. At the same time, the tap duration cannot be so long that it disrupts load function. The tapping duration used in the example shown here was selected so that it does not violate the Information Technology Industry Council (ITIC) curve.

The tapping pattern must also be chosen so that it is minimally likely to be replicated under normal conditions by other system elements, to avoid false or nuisance trips.

## *D. Load Rejection Overvoltage Considerations*

If there is only a small amount of load between a line relay and an IBR, then tapping of that line relay can result in a 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 during tapping of line relay R9. Each time R9 is tapped, there is a transient overvoltage reaching a peak of approximately 1.08 pu. 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. Thus, "tapping" should possibly not be employed on line relays very electrically close to IBRs. However, 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. This would lead to a loss of voltage-regulation capability in the IBRs, resulting in an undervoltage which will trigger other protection systems.

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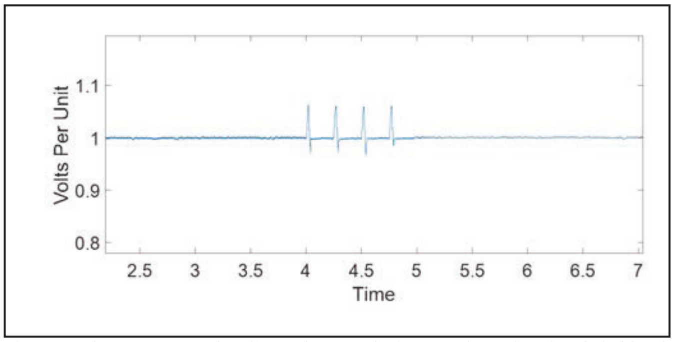


Fig. 9. Voltage measured at line relay R9 during tapping, showing brief load rejection overvoltage spikes.

## VI. Conclusions

In SHePS using only local measurements, detection and mitigation of thermal overloads of conductors during system self-assembly is a significant challenge. This paper has presented a proposed method for addressing this challenge. The 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. Intelligence built into the load relays receives and interprets the modulated voltage signal, and disconnects the lowest-priority loads to alleviate the thermal 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 automatically reconnect, again using only local measurements.

Simulation and testing in PSCAD using the IEEE 13-bus model demonstrated that the tapping method works in the cases tested. 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 of the tapping pattern on various types of loads.

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