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Benefits of Low-Energy Interruption and Low-Energy Testing Technology applied at Transmission Circuits with Falling Inertia

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SUMMARY

This paper presents and discusses the benefits of clearing faults in one cycle followed by testing for the presence or absence of a fault by allowing only one half-cycle of fault current to flow. We refer to these operations as Low-Energy Interruption (LEI) and Low-Energy Testing (LET) respectively. We compare the effects of LEI/LET to conventional multi-cycle interruption and reclosing technology presently applied to transmission systems and include an assessment of these alternatives considering falling inertia due to high renewable penetration levels. Dynamic simulation results using a modified version of the IEEE 39-Bus system model shows the benefits of using LEI/LET technology in a transmission circuit with a high penetration of Distributed Energy Resources (DER), and we expect these benefits to be similarly applicable to any voltage level, such as distribution voltages, as renewable penetration there becomes more and more significant.

KEYWORDS

Falling inertia, synthetic inertia, frequency regulation, security margin, energy curtailment, critical clearing time, distributed energy resources (DER), inverter-based resources, reclosing, transmission faults, low energy interruption (LEI), low energy testing (LET), fast fault clearing, fast reclosing, dynamic simulations.

I. INTRODUCTION

The challenge of falling inertia faces more and more system operators, as market participants of all kinds continue to make carbon neutral pledges. Early adopters, such as ERCOT and Eirgrid have developed new operating practices [1, 2] to deal with it, which includes measures to buy more time for protection and control systems to respond. ERCOT captured the time constraint very effectively in [3], which showed how much faster load reserves have to respond as wind penetration increases and system inertia falls. On the other side of the fence, transmission owners are aware of the need to study critical clearing times to ensure particular generators are not tripped off during a fault. Yet despite this understanding, generator outages resulting from transmission faults persist for both conventional [4] and inverter-based resources [5].

While the role of faults seems understood, most of the activity around inertia mitigation focuses on remedies such as synthetic inertia or lower security margins, which in some ways penalize generators and consumers respectively. Synthetic inertia requires generators to operate below capacity, ramping up quickly to compensate for generation losses. Reducing security margins exposes consumers to greater likelihood of curtailment. Neither seems to be efficient from a market perspective and both add complexity to an already complex problem. For example, a recent study of one fast frequency response (FFR) approach [6] showed that while it mitigated Rate of Change of Frequency (RoCoF) it didn't help frequency. And while new market designs continue to be proposed [7, 8], so far only a few have been introduced.

Despite the acknowledged role of protection, identified in the previously cited references as well as CIGRE Working Groups [9] and IEEE guides [10] on reclosing, a limited new work has appeared in the literature. Most transmission faults are temporary [9, 11], yet reclosing, which could restore full system inertia, is delayed for multiple seconds (in some cases tens of seconds) because of the risk the fault could still be present. In this contribution we will discuss the benefits of two new approaches to protection in low-inertia systems. In combination we believe they could increase market efficiency by reducing the impact of faults in the first place, and then restoring the system quickly having verified the fault is no longer present. Finally, while the studies discussed in this contribution are performed at transmission voltage level, we believe our findings are similarly applicable to sub-transmission and distribution voltage levels.

II. IEEE 39-BUS SYSTEM MODEL DESCRIPTION

A. Original IEEE 39-Bus Model Description

The IEEE 39-bus system model, so-called "New England" test system [12,13], has been extensively used in the power system dynamic literature. The total system load and total generation MW and MVA ratings of the power flow model of the IEEE 39-bus system along with the calculated values of total industry standard and effective inertia of the system model are listed in Table 1.

Table 1. IEEE 39-Bus system's total load and generation ratings, and calculated values of total and effective inertia.

Total PGen (MW)	Total PMax (MW	Total Mbase (MVA)	Total Pload (MW)	Industry Standard H (s)	Industry Standard H (MW.s)	Effective H (s)
6,140	14,535	17,100	6,097	4.6	78,270	10.9

Industry Standard $H(s) = \sum H_i\, MVA_i / \sum MVA_i$
Industry Standard $H(MWs) = \sum H_i MVA_i$
Effective $H(s) = \sum H_i\, Prated_i / \sum Pload_i$

B. Modified IEEE 39-Bus Model

The dynamic model of the IEEE 39-Bus system was modified to simulate a system with behavior more representative of increased renewable penetration at transmission levels. The power flow and dynamic modeling data of the model used to conduct the dynamic simulations were derived from [12].

Some of the conventional generator models were replaced by Distributed Energy Resource (DER) models to simulate various DER penetration levels (e.g., 5%, 10%, 20%, etc.).

Conventional generators operate on their own machine (e.g., GENROU), exciter (e.g., IEEET1), and governor (e.g., IEEEG1) models.

III. INTRODUCTION TO LET

IEEE C37.104 [10] presented a new technology that involves Low Energy Interruption and Low-Energy Testing in which a specialized interrupting device closes its contacts momentarily rather than closing them before re-opening them after a timer expires. In this technology, the current which flows during the momentary close lasts for less than a half a power frequency cycle (i.e., < 8.3 ms at 60 Hz). By analyzing this momentary current the testing device determines whether the fault is still present, and proceeds based on a combination of its deduction and the customer's configuration. In this study we adopt the same circuit testing technique and refer to it as Low Energy Testing (LET). Below, we describe the LET sequence for both permanent and temporary faults.

A. Permanent Fault

This scenario describes a low energy test applied after a permanent fault is detected, cleared, and a test delay time expires. The time intervals associated with the permanent fault case are:

1. Normal load current
2. Fault current starts. Fault is detected and interrupted
3. User-configured delay before initiating circuit testing
4. Low-Energy Test is applied and analyzed.
5. Since fault is still detected, interrupting device is locked out.

Figure 1 illustrates the five time-intervals for a permanent fault case using LET.

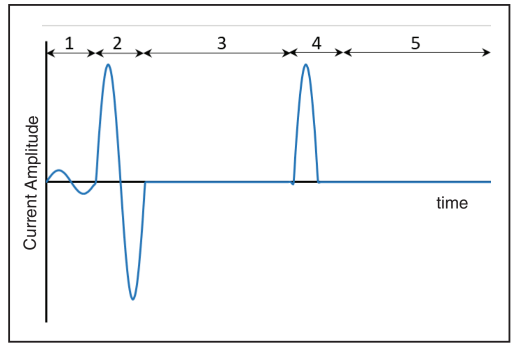

Figure 1. Low-Energy Testing after detecting and interrupting a permanent fault.

B. Temporary Fault

This scenario describes a low energy test applied after a temporary fault is detected, cleared, and a test delay time expires. The time intervals associated with the temporary fault case are listed below:

1. Normal load current
2. Fault current starts. Fault is detected and interrupted
3. User-configured delay before initiating circuit testing
4. Low-Energy Test is applied and analyzed.
5. Since no fault current was detected, breaker recloses and re-energizes loads. For simplicity of modeling, we assume the LET analysis and re-energization operation consume negligible time.

Figure 2 illustrates the five time-intervals for a temporary fault case for LET.

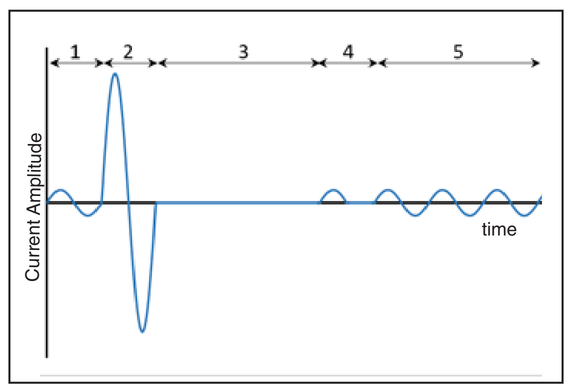

Figure 2. Low-Energy Testing after detecting and interrupting a temporary fault.

For specific details on LEI/LET technology, please refer to the manufacturer's website [14]. Since the fault current flows for a very short time, the fault point absorbs significantly less energy and, hence, we designate this type of event "Low-Energy Testing". We believe the same principle may be applied to transmission circuits where, in addition, it may be used to accelerate the whole clearing, testing and re-energizing sequence.

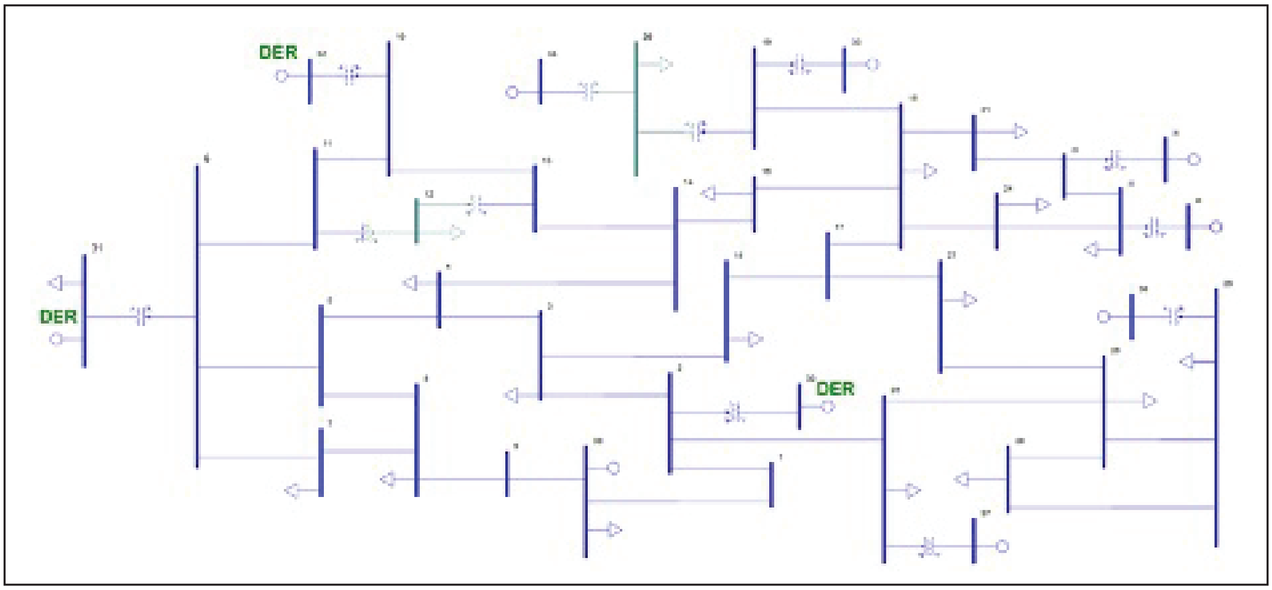

Figure 3. One-line diagram of the modified IEEE 39-Bus system model with 20% DER penetration indicating location of the N-1 contingency.

IV. MODEL DESCRIPTION AND CONTINGENCY SELECTION

A. N-1 Contingency Selection

Automation scripts were developed to apply permanent and temporary faults into every bus on the modified IEEE 39-Bus system model. Each fault is applied and then cleared by tripping an adjacent line (N-1 contingency), implementing all possible bus-line combinations. Then the line gets reclosed after a pre-determined time. For permanent faults, the fault is cleared for the second time by tripping the line and then the circuit breaker locks out. For temporary faults, the fault does not exist when circuit is tested, hence, the tripped line is restored in the reclosing attempt. Dynamic simulation results indicate that generator 38 trips off and reveals the benefits of LEI/LET compared to conventional clearing and reclosing technology. Figure 3 shows the one-line diagram of the IEEE 39-bus system model indicating location of the referenced N-1 contingency at bus 26.

Dynamic simulation results of this contingency using the modified IEEE 39-bus system are provided in Section V of this paper.

B. Generator Model Protection Settings

The voltage and frequency protection settings used for the conventional generator relay models are listed in the following Table 2 and Table 3, respectively. These voltage and frequency settings are per NERC Standard PRC-024-2.

Table 2. Generator voltage protection settings per PRC-024-2.

High Voltage Ride Through Duration		Low Voltage Ride Through Duration	
Voltage (pu)	Time (sec)	Voltage (pu)	Time (sec)
≤1.200	Instantaneous trip	<0.45	0.15
≤1.175	0.20	<0.65	0.30
≤1.15	0.50	<0.75	2.00
≤1.10	1.00	<0.90	3.00

Table 3. Generator frequency protection settings per PRC-024-2 Eastern Interconnection data.

High Frequency Duration		Low Frequency Duration	
Frequency (HZ)	Time (sec)	Frequency (HZ)	Time (sec)
≤61.8	Instantaneous trip	<57.8	Instantaneous trip
≤60.5	10 (90.935–1.45713xf)	≤59.5	10 (1.7373xf–100.116)
≤60.5	Continuous operation	<59.5	Continuous operation

C Load Shedding Relay Model Protection Settings

The underfrequency load shedding (UFLS) protection settings were implemented in the load shedding relay models. UFLS automatically trips selected customer loads once frequency falls below a specified value. These settings are per ERCOT's requirements:

- 5% of System Load Trips at 59.3 HZ
- Additional 10% of System Load Trips at 58.9 HZ
- Additional 10% of System Load Trips at 58.5 HZ

V. DYNAMIC SIMULATIONS

A. Generator Stability

Power system stability issues normally occur due to disturbances in heavily stressed systems. While the disturbances leading to instability may be initiated by a variety of causes, the underlying problem is an inherent weakness in the power system. The challenge of integrating distributed energy sources into the grid brings unique problems such as lower inertia, resiliency, and power quality as the DER penetration increases.

Dynamic simulations were conducted to determine the impact of fast fault clearing (LEI) compared to conventional fault clearing technology on generator stability in power systems with 20% DER penetration or higher.

A.1. LEI vs. Conventional Clearing

Faster fault-clearing is widely accepted as an effective means for improving or maintaining transient stability in utility grids, while simultaneously limiting the let-through current that can damage equipment. Indeed, this is the key reason for establishing critical clearing times. Faster fault-clearing also limits the amount of time that components are exposed to overheating, and the duration of arcing faults that generate sparks which may ignite nearby property. In addition, the inherently tight tolerances in timing required for fast-fault clearing facilitates coordination of protective devices.

Simulation results demonstrate how LEI helps preserve spinning generation due to a bolted fault close-in to a generator bus by detecting and clearing the fault in one cycle. Figure 4 and Figure 5 show the bus voltage (pu) and the generator frequency (Hz), respectively, following a close-in permanent fault.

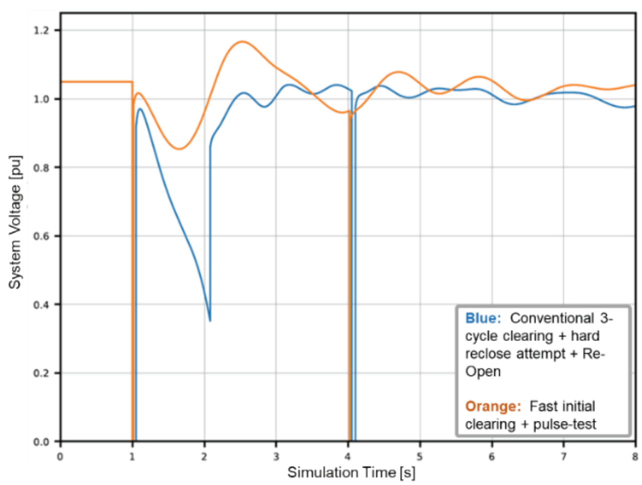

Figure 4. Generator voltage response using LEI/LET (orange curve) vs. conventional clearing (blue curve) following a close-in permanent fault.

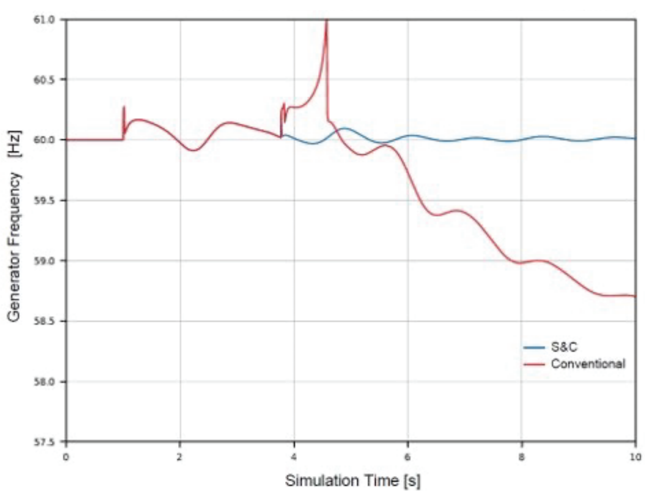

Figure 5. Generator frequency response using LEI technology (blue curve) vs. conventional reclosing technology (red curve) following a close-in permanent fault.

A.2. LET vs. Conventional Reclosing

Simulation results demonstrate how LET helps preserve spinning generation following a bolted fault close-in to a generator bus. Figure 6 and Figure 7 show the generator voltage (pu) and frequency (Hz) following a close-in permanent fault.

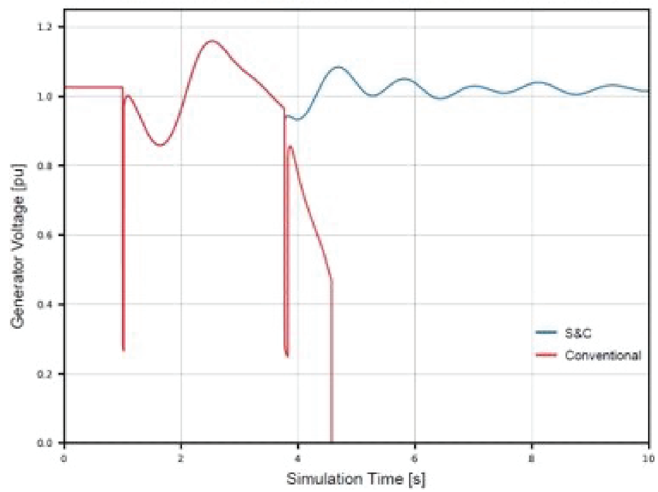

Figure 6. Generator voltage response using LET technology (blue curve) vs. conventional reclosing technology (red curve) following a close-in permanent fault.

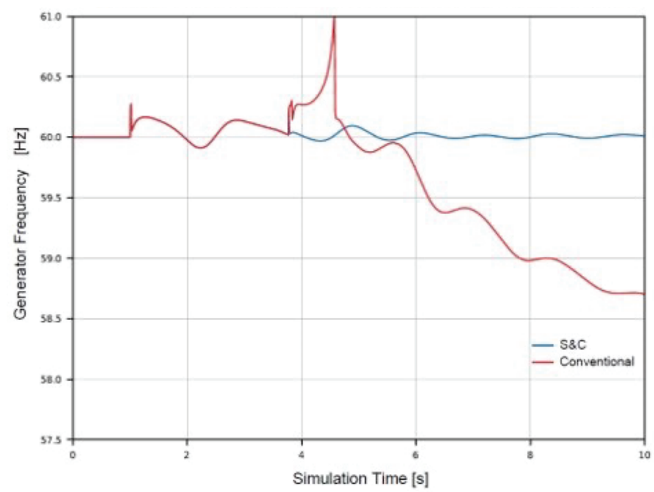

Figure 7. Generator frequency response using LET technology (blue curve) vs. conventional reclosing technology (red curve) following a close-in permanent fault.

In this case, a permanent fault occurs at time t=1 second. Both the LEI technology and conventional protection successfully clear the fault, and the generator remains stable; e.g., the blue line and the red line are coincident until a second event occurs around time t = 3.8 seconds. The LET technology helps with the system response under N-1 contingencies, particularly on the voltage and frequency recovery and damps the oscillatory response on the nearby generators. In this case, LET helps preserve nearby generation while the conventional reclosing causes the nearby generation to go unstable as soon as the permanent fault gets re-introduced.

B. Load Rejection (Load Shedding)

System disturbances can result in a frequency decrease thus causing cascading outages and isolation of areas leading to electrical islands. To prevent extended operation of the system at a very low frequency, load-shedding schemes are implemented to reduce the connected load to allow the frequency to be restored to nominal levels.

Dynamic simulation results indicate that LEI/LET technology helps prevent low frequency load shedding due to a close-in fault near a generator bus. Results for the N-1 contingency depicted in Figure 1 show that for permanent faults, 100% of the load is preserved when LEI/LET technology is used, compared to 89% when conventional fault-clearing and reclosing is used. In this case where there is a relatively low system inertia due to increased DER penetration, LEI/LET technology helps preserve the load while the conventional reclosing causes a significant amount of load losses due to an underfrequency event created right after the permanent fault gets re-introduced.

Figure 8 and Figure 9 show the frequency responses (Hz) following a close-in permanent fault, and a temporary fault, respectively.

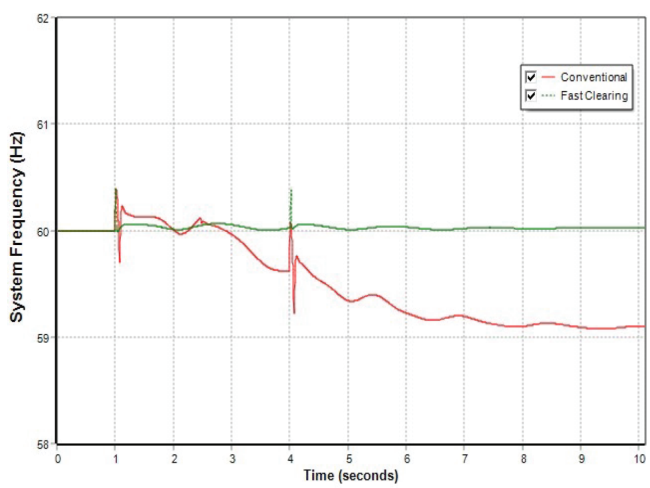

Figure 8. System frequency response following a permanent fault using LEI/LET technology compared to conventional reclosing.

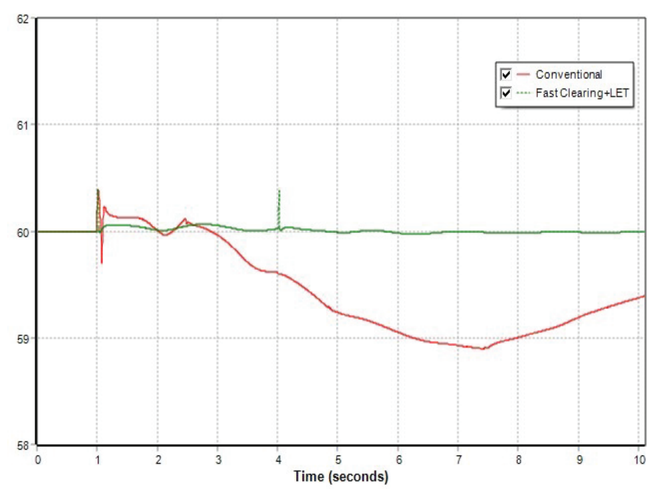

Figure 9. System frequency response following a temporary fault using LEI/LET technology compared to conventional reclosing.

C. Summary of Results

Dynamic simulation results using the modified IEEE 39-Bus system model indicate the benefits of LEI and LET technology when applied to transmission circuits with high DER penetration. When both LEI and LEIT are used during a permanent close-in fault, it was observed that nearby generation is preserved and load-shedding is prevented, compared to conventional fault clearing and reclosing technology. Table 4 shows a summary of simulation results.

Table 4. Summary of benefits of LEI and LET technology applied to transmission circuits.

LEI/LET Feature / Transmission Benefit	Fault	LEI	LET
Preserves generation	**PF**	✓	✓
Prevents load-shedding/load-loss	**PFT**	✓	
Prevents even more load-shedding	**PTF**	✓	✓

PF = Permanent Faults

PTF = Permanent Faults

VI. ROLE OF PROTECTION ON STABILITY

When one thinks of system stability we might expect, intuitively, to see a gradual, or long evolution of generator or system voltage. In fact, in real life in cases from the UK [15], Australia [16], and the US [5], the operation of unit protective elements served to exacerbate the system's transient response, as the operation of protection elements introduced step-function changes in demand or capacity. Such drastic step changes can be seen in Figure 4, where a relatively smoothly varying voltage characteristic is interrupted by the operation of protection elements. In contrast, each case involving LEI/ LET resulted in a system perturbation that was less severe than that due to conventional clearing and reclosing. Not only did this more benign perturbation permit the system to recover faster, and relatively smoothly, it also limited the opportunity for more dramatic voltage or frequency excursions to trip protective elements. That is, LEI/LET avoided introducing step function changes in the trajectory of voltage and frequency.

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protective elements. That is, LEI/LET avoided introducing step function changes in the trajectory of voltage and frequency.

System protection has become increasingly complex, and with the addition of fast-acting inverters, multiple suppliers and proprietary control software, studying and effecting proper system protection will become more difficult. Conventional protection responses may take many cycles, extending to several seconds, to respond: the longer a disturbance persists, the less predictable the protection system's response will be. While this paper has discussed only the immediate effects of fast fault clearing and Low-Energy Testing, we believe it also points to the potential for a faster protective response to mitigate the problem of increasingly complex control systems, e.g. special protection schemes.

VII. CONCLUSIONS

This paper has presented and discussed the benefits of fast clearing, and Low-Energy Testing in a transmission grid with high (20%) DER penetration. We refer to this sequence as LEI/LET. Dynamic simulation results using a modified IEEE 39-Bus system model support the following claims:

- LEI maintains network voltage stability and supports voltage recovery by keeping conventional generators online.
- LET prevents the interrupting device from hard reclosing into a permanent fault, which prevents the loss of generation from reclose attempts which simply re-introduce the fault.
- LEI technology allows higher levels of DER penetration and overcomes reduction in system inertia.
- LET technology can be a key element for maintaining system stability by allowing spinning generation to remain online, especially in "soft", low-inertia systems.
- LEI and LET limit voltage and frequency excursions, which keeps more load connected and prevents the operation of protection elements which introduce step changes in system dynamics

VIII. FUTURE WORK

To further evaluate LEI and LET technology compared to conventional reclosing applied to transmission circuits, the authors would like to conduct additional research to determine the impact of fast reclosing after a temporary fault. The authors believe that fast-reclosing counteracts the voltage disruption caused by longer initial fault-clearing times – e.g., reclosing faster and sooner can compensate for slower initial fault-clearing. In addition, since the dispatch levels of conventional generators impact system stability, it is believed that LEI/LET technology could support higher generation levels while maintaining system stability with lower headroom.

IX. ACKNOWLEDGMENT

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