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# Improving Smart Grid Operation with New Hierarchically Coordinated Protection Approach

Biljana Matic-Cuka and Mladen Kezunovic

***Abstract*— Nowadays, power systems are characterized with heavy loading conditions, abrupt changes in generation patterns, extensive switching of power system configuration and high penetration of distributed generation (DG). Under those conditions performance of the conventional relays that rely on predefined settings may deteriorate leading to system wide disturbances and blackouts. To ensure reliable system operation, monitoring, control and protection have to be improved. In this paper, new Hierarchically Coordinated Protection (HCP) approach to mitigate the effects of increased grid complexity on its operation is proposed. The proposed approach utilizes local and wide area measurements and relies on the three HCP framework levels: fault anticipation and prediction, adaptive fault detection, and relay operation correction in case of unwanted tripping. It brings intelligence to the relays at all voltage levels and uses information and statistics from the systems such as weather, lightning, animal and bird migration patterns, component outage history, etc to enhance protection system tripping dependability and security.**

***Index Terms*— adaptive relaying, distributed generation, neural nets, protective relaying, synchronized sampling.**

## I. INTRODUCTION

DUE to the rise in energy demand and favorable governmental policies a number of DG units have been installed in the power systems. In the last few years, energy from renewable sources has experienced larger percentage growth compared with the energy growth from conventional sources. European Union (EU) heads of states assumed a target of 20 % of energy generated from renewable sources by 2020 [1]. A similar plan for 25 % renewable energy sources requirement until 2025 has been adopted in the US [2]. In the last decade large scale wind generation is being rapidly installed while small scale wind generation has not found broad applications. On the other hand, photovoltaic (PV) systems have slower growth and are evolving from very small residential units to higher generation sizes.

To smooth the DG impact on the grid operation many countries and utility companies have established guidelines while IEC, IEEE and other standard bodies are formulating standards for DG interconnection to the grid. The biggest issue is to make sure that DG operates in a safe environment and that their disconnection will not worsen grid reliability. Depending on their type and technology, size and interconnection point, DGs deployment is specified by the standards and different guidelines, such as the IEEE standard 1547 [3] and FERC order 661-A [4].

Also, the transmission infrastructure upgrade has not followed the increase in electric power generation. Thus, the system now needs to operate with tight margins and less redundancy under dynamic grid operating phenomena such as power and voltage oscillations, as well as voltage, frequency and angular instability. In addition, introducing distributed generation in the distribution system changed its behavior from passive network that transfers power from substation to the customers in a radial fashion to the active network with generation sources causing bidirectional flows and short circuit (SC) current levels that may vary under different circumstances. These new phenomenon may have impact on relay operation since in some situations; conventional relays may not be able to discriminate between fault and normal conditions.

According to the historical data, relay mis-operation is one of the major contributing factors to 70% of the brown out and black out disturbances in the United States [5], [6]. Several cases of inadequacy of relay operation were quoted as possible causes of the disturbances. To prevent tripping due the swing condition, some transmission line relays are armed with the blocking function. However, the relays still may mis-operate for the faults occurring during the power swing period since they are blocked from operation [7]. The distance relay mis-operation in Zone III has caused cascading events leading to major blackout [17]. Protection under-reach, sympathetic trips, unsuccessful clearing of faults and unintentional islanding are all major problems associated with the utilization of DGs in the distribution systems [8]. Study in reference [9] shows that the only way to keep existing distribution system protection philosophy in presence of high DG penetration is to disconnect all DGs instantaneously in the case of the faults, even if the faults are temporary. It would enable the system to capture its radial nature and steady short circuit current levels. However, if such practice continues the system reliability will be deteriorated and DG full potential will not be utilized.

The main focus of this paper is the role of the protection system in mitigating reliable operation of future smart grids. The paper first discusses background of the interconnection standards. The next section reviews the current relaying practices and potential problems. Then the grid protection issues in the modern grids are analyzed followed with the novel protection approach, a case study and conclusions.

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## II. THE GRID INTERCONNECTION STANDARDS

IEEE standard 1547 2003 for Interconnecting Distribution Resources with Electric Power Systems provides requirements for performance, operation, testing, safety and maintenance of the interconnection [3,10]. The requirements are applicable for DGs in 60 Hz system with generation capacity less than 10MW and they should be met at the point of common coupling. The main idea of IEEE-1547 is that DG should not affect operation, protection and power quality of the distribution system and that it should be quickly disconnected under abnormal conditions. Standard does not allow utilization of inverter-based DG control capabilities and it prohibits voltage regulation and reactive power generation. There are eight complementary standards designed to expand upon or clarify the initial standard, four of which are published, and the other four are still in the development phase [11], see Fig 1.

In attempt to maintain integrity of the transmission grid with high wind energy penetration, Federal Energy Regulatory Commission (FERC) proposed low voltage ride-through (LVR) requirements during faults. Order 661-A implies that wind energy sources should stay connected to the grid during most disturbances. The wind plant should stay connected for a grid disturbance resulting in voltage drop of 85% for 625ms time period. Further, the wind plant should stay connected if voltage returns to 90% of the rated power within 3s from the beginning of the voltage drop (see Fig. 2). Moreover the wind plant shall maintain power factor in the range of 0.95 leading to 0.95 lagging at the point of interconnection. To accomplish these requirements, the wind energy source must be equipped with power electronics converters designed to supply such a level of reactive power or fixed and switched capacitors.

Although those two standards have the same objective to smooth DG impact to the grid operation, their requirements in case of the local fault are contradictory; IEEE 1547 requires DG disconnection while FERC 661A expects LVR during the fault. In the case of high DG penetration in distribution systems, simultaneous disconnection of all DGs under some circumstances may reduce system reliability. It may cause incorrect relay operation followed by system wide disturbance, and system instability problem at transmission level due to sudden increase in the load. Thus, the regulators for DGs at distribution level are slowly moving toward wind transmission type performance requirements. FERC 661-A and the emerging new standards for large transmission-connected PV generation still appear to be at odds with the IEEE-1547 standard for interconnection in the distribution system [12]. On the contrary, German BDEW guidelines have imposed a LVRT requirement, automatic real power regulation and automatic mandatory reactive power contribution corresponding to 0.95 power factor.

## III. ISSUES WITH CURRENT PROTECTIVE RELAYING APPROACHES

The main goal of protection relay is to quickly and reliably detect the fault and disconnect the faulted area. In the case of transmission lines, relays should differentiate the internal faults from external faults so that only the faulted line is removed, provide the exact fault type selection so that advanced tripping and reclosing can be applied, and locate the precise fault position on the line so it can be repaired and restored quickly.

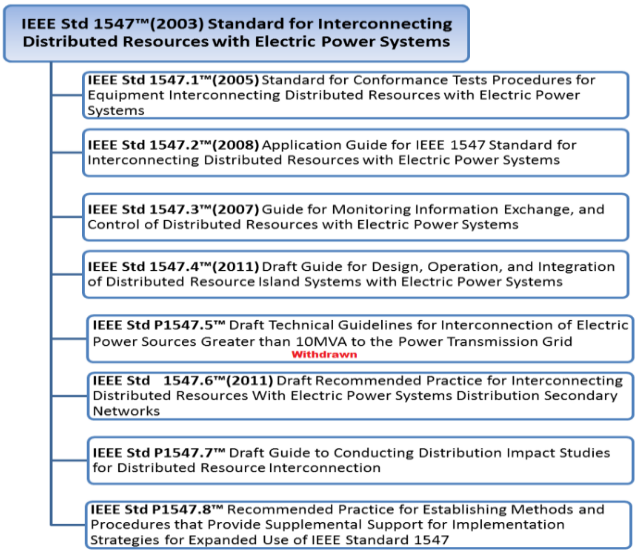

Fig 1. IEEE 1547 2003 Standard Series [11]

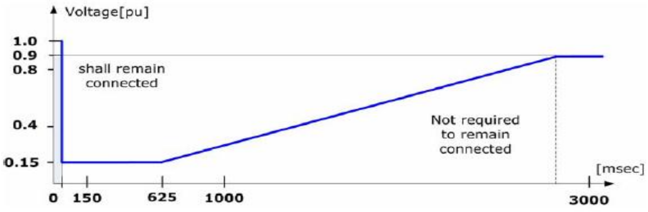

Fig 2. Required wind plant response to emergency low voltage by FERC 661-A [13]

The traditional operating principles of the conventional relays as classified in [14] may have some selectivity and reliability of operation issues:

- Magnitude Relays: The operating logic of such relays is based on the comparison of the magnitude of one or more operating quantities to the threshold. For example, the overcurrent relay responds to the changes in the magnitude of the input current, over/under voltage and frequency relays responds to the changes in voltage and frequency. Such relays are sensitive to the major changes in relay quantities that are caused by normal system operation rather than the faults since in that case the safety margin for differentiating between the faults and normal operating conditions may be significantly reduced, as discussed in section IV.b.
- Directional Relays: The operating logic of such relays is based on the comparison of the phase angle between two AC inputs. The comparison can be based on current and voltage phasor, or only on current phasors. Such relays if based only on current flows may create false fault detection due to bidirectional power flows, as discussed in section IV.D
- Ratio Relays: The operating logic of such relays is

based on the comparison of the ratio of two phasors to the thresholds. An example of a ratio relay is the distance relay. This relay may get confused with current in-feed and voltage variation phenomena such as power swing or sudden increase in the load. An example of the relay mis-operation is shown in section VI.

- Differential Relays: The operating logic of such relays is based on the algebraic sum of two or more inputs. In a general form, those inputs may be the currents entering (or leaving) a specific protection zone. They are sensitive to different no-fault distortions in the currents such as inrush currents due to component switching or distorted currents due to instrument transformer saturation
- Pilot Relays: The operating logic of such relays is based on the communicated information obtained from the two ends of the line. The decisions made by a local relay and by a remote-end relay are combined to form the final decisions. The inside principle of each relay could be any of the four types described above. Such relaying principle is sensitive to the errors in the communication system.

All conventional relays have in common that they operate as a tradeoff between security (not to trip when there is no fault) and dependability (to trip when there is a fault), with the bias toward dependability. This tradeoff in internal logic makes protective relays mis-operate since the conventional relays have predefined settings that cannot be changed online following the system change that requires a change in the tradeoff bias. The settings are calculated assuming the worst case system conditions and cannot be easily altered when such conditions are changed to different worst case scenarios. Due to the complexity in system operation, such as change in topology or loading, the relay decision drawn using only one feature, such as current magnitude may be is insufficient to make accurate decision in the systems with high DG penetration.

## IV. OPERATION ISSUES IN A MODERN GRID

The following sections summarize issues in the modern power grid with high penetration of renewable DGs:

### A. Anti-islanding

The islanding occurs when a part of the utility network is still energized by the DG while being disconnected from the main grid. In this situation, neither the voltage nor the frequencies are controlled by the utility. Normally, islanding is the consequence of a fault in the network. If DG continues its operation after the utility supply was disconnected, faults may not clear since the arc is still charged. The main problems associated with unintentional islanding are: unacceptable limits for voltage, frequency and other power quality parameters which may lead to damage of network and customer equipment, out -of-phase reclosing that may cause high transient inrush currents which may damage the generator and electric shock to utility workers by touching energized conductors.

### B. Short Circuit Level

Connection of DG to power grid has various impacts on the performance of the existing protection schemes. The impact depends on DG type, size and location, impedance and configuration of the line. DGs contribute current to the circuit and their contribution may rise, lower or change direction of the short circuit (SC) current. Machine based DGs inject SC current levels of more than 5 times their rated current and may contribute to the short circuit current for long time due to high inertia. On the other head, the inverter based DGs have lower contribution up to 2 times rated current and trip off very quickly due to low inertia. If, for example, a remote part of a distribution network is equipped with large inverter based DG installations, it could happen that in case of a failure there is almost no significant rise of the phase current and the fault is therefore not detected by the overcurrent protection system. With DG in the network, the fault impedance can also decrease due to parallel circuits, therefore the SC current level increases and there could be unexpected high SC currents in case of a failure.

### C. Power Quality

The power quality problems due to DG penetration are applicable to the distribution and medium voltage grids. Transient voltage variations can be expected if there are relatively large current changes during connection and disconnection of DGs. Two aspects of power quality usually considered to be important during evaluation of DG impact on system performance are: voltage flicker conditions and harmonic distortion of the voltage. Depending on the particular circumstance, a DG can either decrease or increase the quality of the voltage received by other users of the distribution network. The effect of increasing the grid SC current by adding generation often leads to improved power quality; however, it may have a negative impact on other aspects of system performance. A single large DG, or aggregate of small DG connected to a weak grid may lead to power quality problems during starting and stopping conditions or output fluctuations. For certain types of DGs, such as wind turbines or PVs, power fluctuations are a routine part of operation due to varying wind or sunlight conditions.

### D. Reverse Power Flow and Voltage Profile

One of the most important responsibilities for the utility is to keep acceptable voltage range in distribution systems. The inverter-based DGs may regulate voltage at point of common coupling (PCC). However, according to the IEEE standard 1547 inverter-based DGs are not allowed to regulate voltage at the point of common coupling (PCC). The tap-changing transformers or switched capacitors are used instead. The inverter-based DGs are designed to operate only at unity power factor because this condition will produce the most real power and energy. This limitation is a matter of standardization and agreements, and it is not technical one. Generally, inverters have the capability of providing reactive power to the grid in addition to the active power.

Introducing DGs at the load side reduces the load demand and in turn leads to reduced losses and improved voltage profiles on the feeder. This is a true statement as long as the DG generation coincides with the substantial load demand so that the net power flow remains going from the substation to the load. As the penetration levels of DG rise, there may be time periods during the day when the power flow is from the load towards the substation, a situation not normally anticipated in the distribution system design. This will affects performance of standard protection schemes with directional overcurrent relays.

Voltage regulation and voltage rise are the key factors that limit the penetration level of DG that can be connected to the system. During heavy load conditions, with connected DG, voltage levels may drop below acceptable limits. The main concern about high DG penetration levels in distribution systems is the effect of the expected large randomly fluctuating real power output from these sources. Fluctuating power from DG generators can cause the feeder voltage profile to change, possibly increasing the switching operations for line regulators and capacitors.

## V. PROPOSED HIERARCHICALLY COORDINATED PROTECTION (HCP) APPROACH

A new HCP paradigm for smart grids is envisioned to be able to deal with the grid behaviors that have not been seen before but is anticipated in the future: heavy loading conditions, abrupt changes in generation patterns, extensive switching of power system configuration and high penetration of distributed generation. This will lead to an equal importance of balancing the dependability and security of protective relay operations, which is hard to achieve simultaneously since in the past designing protection systems for selected tradeoff between dependability and security, was common. The new protection approach is proposed to avoid relay mis-operations that may lead to blackouts. The framework of the proposed approach consists of the:

- Predictive protection. The statistical data and information from weather related tracking systems, history of the component outages, and power system operating conditions that may lead to the major disturbances, etc are used to anticipate occurrence of a fault condition. The local protection is "armed" to respond with specific tripping logic for each disturbance that is anticipated.

- Inherently adaptive protection. It adjusts its tripping logic based on feature patterns of waveform measurements that are recognized online and matched to the patterns obtained during learning process that includes thousands of potential fault conditions.

- Corrective protection. If local protection mis-operates, accurate and fast fault location/analysis restores the system component(s) quickly if the original tripping action is determined not to be correct.

This approach may be utilized at all power system levels and any robust and reliable protection scheme may be defined and developed following these three concepts. The following sections describe proposed approach for transmission and distribution system using such concepts.

### A. *Transmission System*

An example of the novel transmission system protection philosophy that relies on local and wide area protection methods is presented in this section. This approach allows automated system-wide monitoring of system component condition, which assures reliable protective relay operation and performs corrective actions in the case protection dependability or security is compromised. The scope of the proposed approach includes:

Predictive Protection: The system monitoring and control tool that performs routine vulnerability analysis of operating condition of the whole system and individual elements [15] is deployed at the control center level and alert signals are sent to the substation level to closely monitor relays placed at the most vulnerable components. The prediction of where the protection mis-operation may occur gives an early warning of how the contingencies may unfold.

Inherently adaptive protection: At the substation level a neural network based fault detection and classification algorithm is employed [16,17] . Its tripping logic is based on feature patterns of waveform measurements. This approach does not have settings and hence avoids mis-operation due to inadequate settings allowing for an inherent adaptive action to optimize the balance between dependability and security

Corrective protection: At the substation level, fast and accurate synchronized sampling based fault location [18] and event tree analysis [17] to detect incorrect line tripping sequence and incorrect relay logic operation respectively are deployed. Upon transmission line tripping, fault location algorithm will validate correctness of relay's operation and in case of unconfirmed fault condition; the system component (transmission line) will be quickly restored. The relay logic will be checked as it executes and if an incorrect sequence is detected, the relay action will be corrected.

As a summary, the three concepts proposed earlier are tied together in an overall solution design shown in Fig.3.

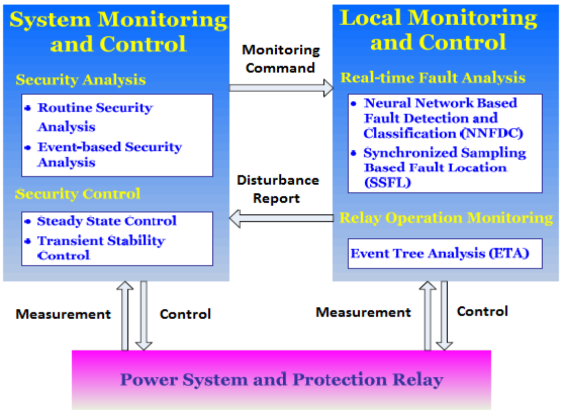

Fig. 3: The Hierarchical System Protection Architecture

### B. *Distribution System*

The proposed framework may also be used in defining new protection scheme for distribution system. It is well known that existing protection practice with overcurrent relays in cases of high DG penetration is ineffective due to problems in finding right settings and time-coordination. It appears that more sophisticated and adaptive methods have to be developed.

The weather tracking and prediction models have been used in the power systems to enhance the performance of planning, scheduling, energy management, and feedback control systems [19]. However, utilization of such solutions in designing the protection system has not been explored yet. The lightning and severe weather conditions are major cause of the faults in distribution system. The information from the weather satellites may be used to develop alerts to potential protection scheme and certain strategies to better isolate the faults in the network.

Since fuses cannot be coordinated and controlled by external signal, they will lose their function in the system with high DG penetration. The protection system must rely on breakers and reclosers that will communicate with the main relay located in the substation. The relay would sense the fault, identify the faulted section on the feeder, and isolate the faulted zone by tripping appropriate breakers. This way, the remaining zones can still function as usual. The relay could be designed using advanced machine pattern recognition technique to be able to distinguish between fault and normal condition under any circumstances.

As a part of the corrective strategy, a fast and accurate fault location may be used [22]. In addition, highly accurate distribution system fault location is possible by combining lightning location data form the U.S. National Lightning Detection Network with fault monitor disturbance data and distribution feeder location (GIS) data [20]. The data latency is several seconds and may be used in the corrective protection to verify the fault location determination in the system. Moreover, animals and birds cause large number of outages in overhead distribution systems. The frequency of animal and bird related outages depend on the area, season and time of the day. The historically obtained outage patterns and animal/bird migration patterns may be used to verify the fault location determination in the distribution systems [21].

## VI. CASE STUDY

In order to illustrate the use and operational efficiency of the proposed Hierarchically Coordinated Protection scheme for the transmission applications, the IEEE 39-bus New England test system shown in Figure 4 is utilized [23]. The two most vulnerable lines according to their vulnerable indices are: Line 21-22, 28-29 [15]. The outage of those lines will have a large impact for the system stability since the original loads in those two lines will be redistributed to the neighboring lines causing more overloading issues. The system monitoring tool will inform the local relay monitoring tool on those lines to monitor the relay operations closely.

Assume a series of disturbances occur in the system, with the event sequence shown in Figure 5. The related system components are marked in Figure 4. These two faults are permanent faults and thus isolated by the relay actions. After the line 21-22 is removed due to the first fault, the top 2 most vulnerable lines are changed to: Line 28-29, 2-3. After the line 28-29 is removed due to the second fault, the top 2 most vulnerable lines are changed to: Line 23-24, 26-29.

This contingency may cause relay at Bus 26 of Line 26-29 to mis-operate. The trajectory of impedance seen by that relay is shown in Figure 6 with the event sequence labeled.

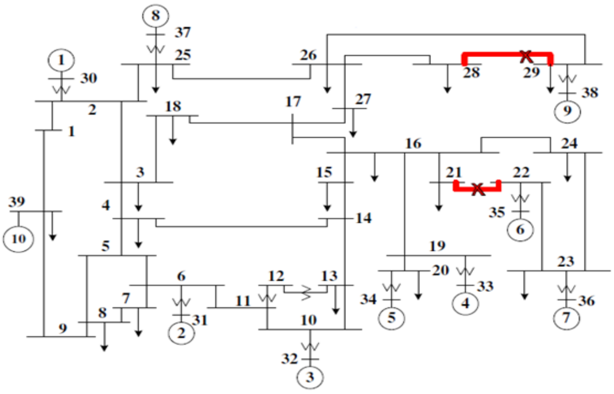

Fig. 4: IEEE 39-bus system

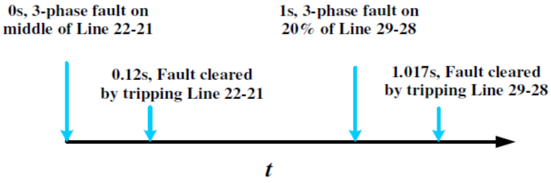

Fig. 5: Event Sequence

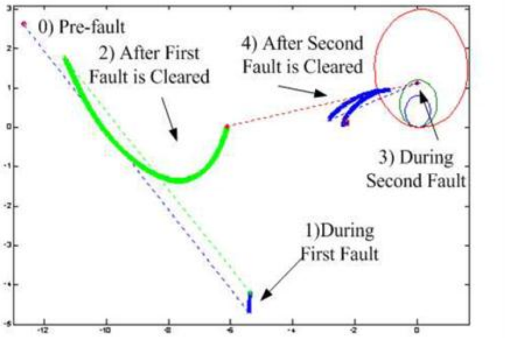

Fig. 6: Trajectory of Impedance

Although the two faults are not related to the healthy line 26-29, the power swing caused by the two faults will have an impact on the distance relay. It observes Zone 3 fault at 1.627s after the second fault clearing until the trajectory leaves Zone 3 circle at 1.998s. The distance relay may trip Line 26-29 when its Zone 3 timer expires. As a result, buses 29, 38 will be isolated from the system, including the G9 and loads at bus 29. This will results in the oscillation in the rest of the system and further cascading outage may happen.

The mentioned situation can be prevented by the proposed system and local monitoring and protection tool. When the first fault occurs, the faulted line 21-22 is removed and no other operation happens. The relay monitoring tool for the relay at Line 21-22 will inform the system monitoring tool about the relay operation for the three-phase fault. The system security analysis is activated after the first fault. An alert signal will be sent to the local relay monitoring tool at vulnerable lines at this stage. Since the first fault will not degrade the system stability very much, the local relay monitoring tool will not be authorized to intervene with relay operations at this stage. When the second fault happens and Line 28-29 is removed, the local relay monitoring tools for the most vulnerable lines 23-24 and 26-29 will be authorized to correct the potential relay mis-operation or unintended operation in real time since the mis-operation of those relays will directly separate the system. After the second fault, the local relay monitoring tool at Line 26-29 will draw a conclusion to block the relay from tripping for Zone 3 fault. That information will be sent back to the system. The system will issue appropriate control means to mitigate the disturbances. In an actual large scale system, it is impossible that one or two contingencies like the ones discussed in this scenario can cause large scale system oscillation. Usually there is enough time for coordinating the system-wide and local analysis in the initial stages of the disturbances to mitigate the impact of the disturbances before they unfold into the large one. An interactive system-wide and local monitoring and control means can really help reduce the probability of a cascading blackout since the disturbances can be fully analyzed at both the local and system level.

## VII. CONCLUSION

In this paper, new protection approach for modern power systems is presented. It is shown that proposed three layers approach could be crucial in monitoring, detecting, and locating the faults in distribution and transmission systems. The proposed prediction methods provide necessary “breathing time” for protection system to adjust bias between dependability and security for each disturbance and to reduce relay mis-operation rate. The advanced “setting-less” fault detection methods are utilized. Without calculating the phasor, the voltage and current signals from the local measurement are formed as patterns using time-domain data samples. Without need to specify settings, the setting coordination work can be avoided. Moreover, online relay operation verification tool is provided. The relay operation is constantly monitored and its correctness is checked. In the case of the incorrect relay operation the power system component is restored online.

## VIII. ACKNOWLEDGMENT

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