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Wide-Area Measurements-Based Out-of-Step Protection System

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***Abstract* – From time to time a sequence of unexpected and often overlapping contingencies may lead to power system angular instability and even blackouts if not addressed adequately by means of out-of-step protection system. This paper proposes the out-of-step protection system structure, which is based on generation sources electromotive forces vectors angle control. Protection system consists of several, strategically located terminals, exchanging with information in real-time by means of communication network. Protection system structure, principles of operation and implementation problems addressed in the paper, as also IEC 61850 communication standard-based implementation described.**

***Keywords* – Power system, out-of-step protection, synchronized measurements, IEC 61850 communication standard.**

I. INTRODUCTION

Power system is always a subject to various small and large disturbances during the steady state operation. System engineers and planners try to design the most reliable power system structure, which is able to cope with all possible contingencies. But minor probability do exists, when unpredicted scenario of complex event may lead to power system instability. One of the most dangerous power system instability conditions is angular instability, often referred as out-of-step (OOS) regime or asynchronous operation (AO). When generated power cannot be successfully delivered to the load (because of the transmission line limited capacity, short circuits, insufficient generation), then, in response to the generation/load imbalance, some part of the power system generators starts operate asynchronously with remaining part of the system. OOS regime cannot be tolerable for prolonged period of time due to negative impact it has on system equipment and system integrity. Dedicated OOS protection system should respond on AO, acting on power network splitting in predetermined location with a goal to preserve the generation/load balance within each peninsula. All types of OOS protection systems can be divided on [1]:

- Protection of local type, which uses locally available measurements for OOS regime detection;
- System-wide measurements-based OOS protection, which uses measurements from several location within power network.

This paper presents new approach for OOS regime detection where the wide-area measurements technology is combined with modeling technique. Protection system structure and possible IEC 61850 communication standard-based implementation are under consideration.

The rest of the paper is organized as follows. Section II deals with a theoretical and technical background of the OOS protection. Section III reviews a proposed new principle of out-of-step protection. Section IV and V presents the implementation of the new protection system using IEC 61850 communication standard. Finally the conclusions are drawn in Section VI.

II. OUT-OF-STEP PROTECTION BACKGROUND

Out-of-step relaying philosophy and methods are well known and established. The main objective of any OOS protection system is to detect power system AO at the early stage, then take some preventive actions (force generators excitation or generators dynamical braking, shed load, etc.) and, if all preventive actions has no desired effect - OOS regime is still developing, than OOS protection should split the network on several asynchronously rotating parts. Power system splitting accomplished by means of tripping several transmission lines (TL) which interconnects parts of the network [2], [3]. Controlled splitting should take place in predefined locations with the expectation that generation/demand balance within each island could be preserved by the action of local automation systems.

At least several OOS detection methods and algorithms are known and used with more or less success [2]-[4]:

- Distance algorithm-based methods;
- Ucosφ algorithm;
- Energy function-based method;
- Angle control-based methods.

Not all methods find their practical implementation, but distance algorithm-based and angle control-based methods are widely used. Distance algorithm-based OOS protection typically incorporated within line distance protection terminals, uses only locally available measurements and monitors the way the impedance trajectory crosses the protection zone [5]. The main drawback of the method is that protection controlled impedance not necessarily enters protection zone in case of OOS regime. Thus, the preferable network splitting place and protection response hardly can be coordinated.

Angle control-based method relies on detection of the angle difference between two voltage phasors, sampled at critical network locations. OOS protection operates when angle difference exceed the maximum allowed value. Angle control

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method is used in OOS protection described in [6]. Protection models voltage phasors $\underline{U1}$, $\underline{U2}$ of equivalent generation sources for two-machine network (Fig. 1) and monitors angle difference and angle difference rate of change according with formulas (1). Settings *C1, C2, C3* and *C4* define protection operation conditions. The effectiveness of protection operation is highly dependant of the voltage phasors modeling precision. The main drawback of the protection is inability to adapt protection equivalent impedances setting $\underline{Z}k1$, $\underline{Z}k2$ to current network configuration and regime of the power system.

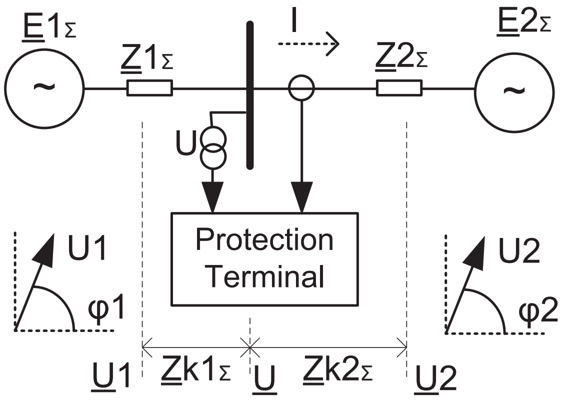

Fig. 1. Angle control-based OOS protection with local measurements and voltage phasors modeling.

$$\begin{aligned} \underline{U}1 &= U + \underline{I} \cdot \underline{Z}k1 \\ \underline{U}2 &= U + \underline{I} \cdot \underline{Z}k2 \\ \sigma &= \varphi1 - \varphi2 \\ C1 &< \sigma < C2 \\ C3 &< \frac{d\sigma}{dt} < C4 \end{aligned} \qquad (1)$$

Another approach intended to cope with system-wide disturbances often referred as Wide-Area Protection Systems [7], [8]. This system uses measurement from several, geographically distant power network locations. All measurements are synchronized, time-stamped and delivered to the main control center for further processing. The basis of such system is Phasor Measurement Units (PMU) which samples local currents and voltages and transmit calculated phasors to the main control center where decision is taken (Fig. 2). Such centralized system assumes that decision making computer is operating in real-time, communication network is reliable and has high throughput rate. Despite the fact, that OOS condition is much slower process comparing with other transient processes, the PMU-based OOS protection may be limited in functionality because PMU's insufficient data transmissions rate (20 – 60 samples per second).

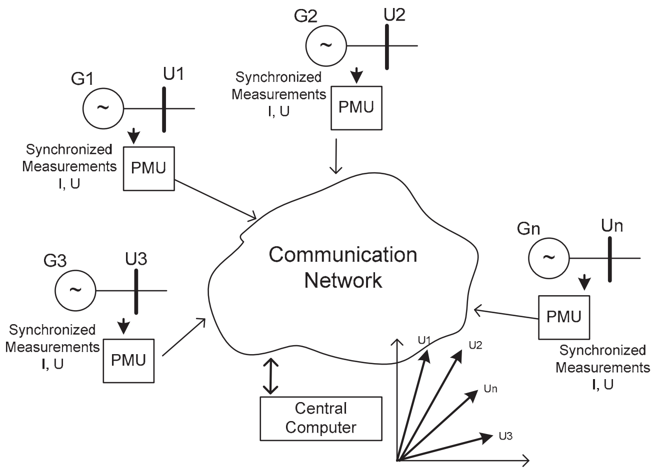

Fig. 2. Centralized PMU-based Wide-area protection system.

III. PROPOSED OOS PROTECTION STRUCTURE

The new proposed OOS protection system combines both principles: wide-area measurements technology and local device-based decision-making. The system consists of several protection terminals (Fig. 3) each monitoring generation sources currents and voltages at the station bus. Each terminal models equivalent generator electromotive forces (emf) vectors according with formula (2). It is supposed that $\underline{E}gn$ is equivalent emf. of the power station which, in turn, consists of several generators units.

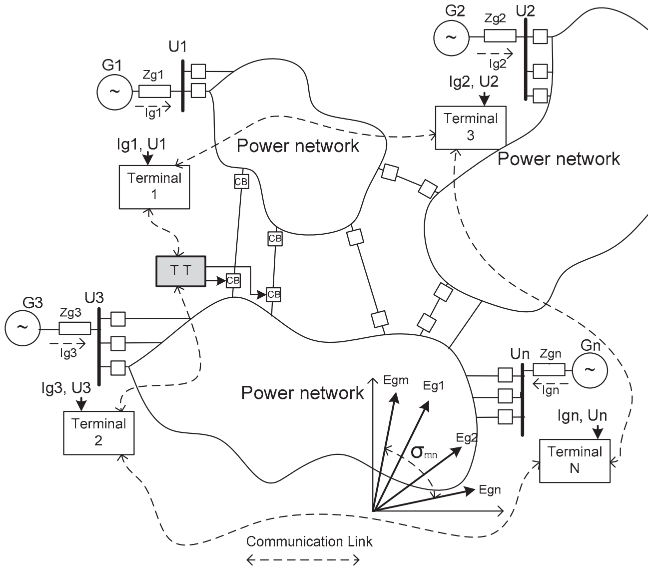

Fig. 3. Proposed OOS protection system structure.

$$\underline{E}gn = \underline{U}n + \underline{I}gn \cdot \underline{Z}gn \qquad (2)$$

where $\underline{E}gn$ – equivalent emf of the *n* generation source;
$\underline{U}n$ – voltage at the station bus;
$\underline{I}gn$ – generation source total current;
$\underline{Z}gn$ – generation source equivalent impedance.

Alternatively, more detailed approach for generation source emf modeling also possible. Then terminal calculates not only equivalent emf $\underline{E}1$ of the power station, but emf for each generator $\underline{E}1.1, \ldots, \underline{E}1n$ could be modeled additionally (Fig. 4).

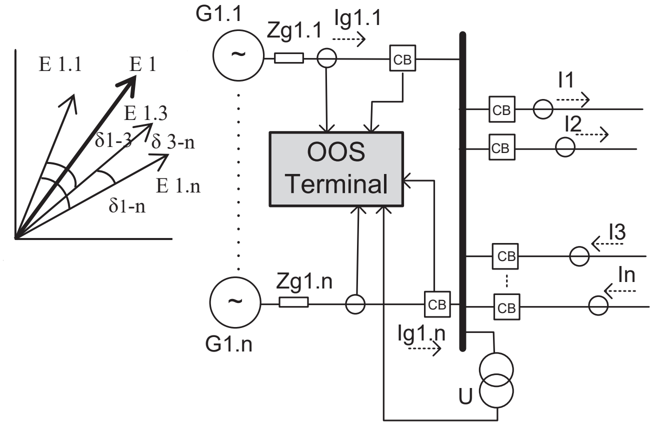

Fig. 4. Terminal calculates power station equivalent emf *E1* and each generator emf *E1,...E1.n*.

The number of possible angle differences increases significantly in this case (angle difference for each pair of generators should be calculated), but, at the same time, this approach will allow recognize and localize the AO regime at the early stage and take appropriate actions for each individual generator. Terminals exchange with calculated emf. phasors in real time by means of high speed communication network. The measurements of all terminals (currents and voltages) should be synchronized within several microseconds and time-stamped by means of GPS disciplined station clock. Upon completion of the information exchange cycle, the emf vectors of all generation sources are available for each terminal. Terminals calculate the angle difference between appropriate voltage vectors and the angle difference rate of change according with formulas (1). The angular difference can be calculated between each pair of available emf vectors or, the required pair of vectors may be defined with appropriate setting for each terminal. Terminal produces the trip signal when out-of-step condition is detected according with formulas (1). Trip signal can be generated locally (by internal relay of the terminal) if terminal located in close proximity with power system splitting place. Otherwise, circuit breaker trip command should be transmitted to the remote destination terminal (TT) by means of the communication network.

IV. IEC 61850 COMMUNICATION STANDARD

The IEC 61850 is modern communication standard for power system substations and now being widely used in practical applications. The first edition of the standard was generally concerned with substation operational aspects regarding the protection and control. The second edition of the IEC 61850 "Communication networks and systems for power utility automation" provides new data objects and definitions witch further extends the standard functionality to keep high quality and reliability of power systems [9]. The main advantage of the communication standard is that it supports all possible structures by means of defining [9], [10]:

- Standard Data Objects for all monitored values;
- Standard Communication Services;
- Fast and reliable Communication protocol;
- Standard Configuration Language to specify all types of information and functions.

This has been achieved through a breakdown of all substation functions into their smallest pieces relevant to communication (logical nodes) and a consistent application level object modeling of the logical nodes. Substation hierarchical structure which maximally benefits from IEC 61850 communication standard implementation presented on Fig. 5. Substation levels are interconnected by means of two communication buses: process bus interconnects the field level (level of analogue and binary input/output signals) with IEDs (intelligent electronic device) and station bus interconnects all participating IED on bay level. The higher inter station communication also available.

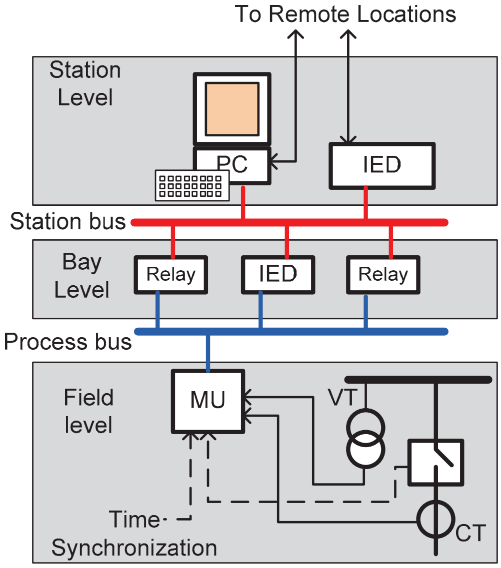

Fig. 5. IEC 61850 standard-based substation hierarchical structure.

IEC 61850 standard supports two communication services dedicated to data exchange through the process bus and station bus [10], [11]. Merging Unit (MU) is the source of the information in digital form at the process level. MU is an interface unit that accepts analogue and status signals from the process level equipment and outputs time-synchronized sampled values by means of the unidirectional multi-drop digital data stream using IEC 61850-9-2 "Sampled Value" (SV) communication service. Two sampling rates are defined for the MU: 80 samples/period (for protection purposes) and 256 samples/period (for metering). The SV data transmission technique operates according with publisher/subscriber model. There either can be a single subscriber (Relay or IED) or multiple subscribers on MU published data. Multiple Relays and IED's exchange with information at the station bus level implementing the "Generic Object Oriented Substation Event" (GOOSE) communication technique [11]. The purpose of GOOSE message is transmission of various substation events defined by a specific data set. GOOSE messages also uses publisher/subscriber model thus allowing multiple IED's and Relays operate in coordination.

The next, upper level of information exchange – inter-station and station-control center communication is not yet completely defined by IEC 61850 standard but the general requirements and guidelines for the selection of communication services and architectures compatible with IEC 61850 already presented.

V. IEC 61850 COMMUNICATION-BASED OOS PROTECTION SYSTEM

The IEC 61850 communication standard-based implementation can vastly improve the proposed OOS protection system in terms of complexity reduction and hardware minimization as also protection system functionality can be easily expanded in the future. The problem of analogue and status signals hardwiring and control for several generators can be solved implementing the SV communication technique within the power station process bus (Fig. 6). Here OOS protection terminal controls all power station generators by means of subscribing to each generator MU's SV data. Thus, terminal is provided with all necessary information (generators currents, bus voltages and generators status information). Additionally, information about outgoing transmission lines circuit breakers (CB) status (on/off), transmission lines currents values *I1, I2,…In* also available for OOS terminal as a subscriber and may be further used for network topology recognition as also may help to coordinate the power system splitting place considering existing power network configuration.

At the station level, OOS terminal may benefit obtaining information from protection relays and various IED's by means of subscribing on GOOSE messages from relays of interest. The main point here is the availability of the information about short circuits and other unbalanced conditions of the network. OOS terminal does not need anymore trace the unbalanced regimes of the network because this information available from the neighbors relays.

As shown on Fig. 3, the proposed OOS protection system uses dedicated communication link between terminals (similar to what line current differential protections are using). Reliable inter-station communication is a critical part for the proposed OOS protection system. The present scope of IEC 61850 standard is limited to data exchange within substation [10]. Some attempts are made to adapt the existing IEC 61850 communication services and models to wide-area communications structures [12]. The main problem here is that wide-area communication bandwidth between substations is limited (typically 2 Mbit/s), which is far less than 100 Mbit/s Ethernet bandwidth between IEDs in substation. At the same time, it is supposed, that amount of information OOS protection system exchanges in real-time will not overload communication network capabilities (in contrast with line current differential protection, OOS protection data can be transmitted much rarer because of the AO process slower nature).

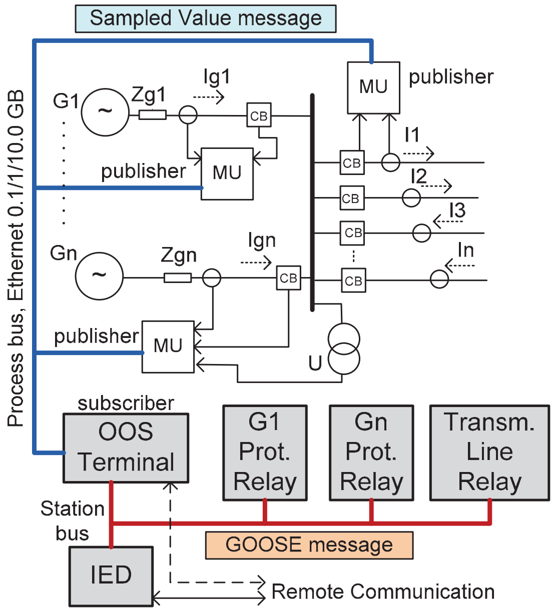

Fig. 6. OOS protection terminal control generators signals using IEC 61850 communication.

IEC 61850 GOOSE technique can not be used directly in this case because GOOSE is event-driven message. The SV messages, specified in IEC 61850-9-2, could offer a solution when extended to inter-station data transmission [11]. Inter-station communication and communication between substations and control center are covered by IEC61850-90-1 and 90-2 part of the standard (some parts are under development). IEC/TR 61850-90-1:2010(E) document provides a comprehensive overview on the different aspects that need to be considered while using IEC 61850 for information exchange between substations.

VI. CONCLUSIONS

The proposed structure of the OOS protection system will benefit from both approaches: wide-area information availability and decentralized, real-time decision-making. Protection system covers the whole power system network and thus is much less susceptible to network configuration rearrangements, generation/demand influence and power system regime variations. Protection terminals have all the available information about generation sources and, thus, protection system operational algorithm can be adapted even to very complex patterns of asynchronous regime. Practical implementation of the proposed protection system clearly benefits when IEC 61850 communication standard is considered.

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