Power Restoration in Medium Voltage Network Using Multiagent System

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Abstract. *The article describes a novel approach to a power restoration in medium voltage power distribution network. It focuses primary at searching of a new network configuration enabling to minimalize the size of faulted area and to restore the power for the highest possible number of loads. It describes characteristic features of medium voltage power distribution network and discusses the implementation of the presented approach in existing networks. A software tool, developed by the authors, including physical simulation of model network and its autonomous control system is described. An example of fault situation in a virtual distribution network is presented. Afterwards, the solution of restoration problem by proposed multiagent system is simulated using the software tool described in the paper.*

Keywords

Autonomous agent, autonomous control, medium voltage network, multiagent system, power system restoration.

1. Introduction

The control of electrical distribution network includes mainly switching elements manipulation, voltage regulation, fault locating and restoration, and taking care of components lifespan and reliability. These jobs can be overall called as supplying required amount of electricity to customers having required parameters.

An autonomous control system is one of the options to make control of power distribution networks more effective. It keeps all the knowledge gathered during systems operation and uses it in various situations. It has to be able to solve some typical fault situations without the action of dispatcher. In case of more complicated and extensive problems it can receive a large amount of data and perform necessary calculations needed to find possible solutions. A dispatcher is then responsible just to make a final decision. Sometimes, the amount of information available to autonomous control system is not sufficient to solve the problem. In such a case, dispatcher has to use his knowledge and experience to add missing data or to answer a particular question. This data or answer is needed to proceed, if the certainty of correct action, proposed by autonomous system, is not high enough, or system cant propose any solution without a proper answer.

Main advantages of autonomous control are incomparable higher processing of measured values and fault alarms, ability to perform calculations and to use rules in order to solve the most typical fault situations. Finally, it lightens a dispatcher from low level routines and it enables him to use its abilities for more difficult and complex problems [1].

2. Methods of Power Restoration

2.1. Theoretical Approach

When the power supply is interrupted by a fault, it is necessary to perform network reconfiguration in order to minimize the number of customers affected by loss of power. The problem of obtaining a new configuration is referred to as power system restoration. To obtain the new configuration, various approaches have been proposed, which can be roughly classified into four categories: heuristic methods [2], expert systems [3], mathematical programming [4] and soft computing [5].

Heuristic methods and expert systems are often used in industry. However, in the true sense they dont always provide the optimal solutions. Mathematical programming is able to obtain optimal solution after the formulation of the problem, but it needs some engineering judgment in formulating restoration problems due to their complexity. Also its long execution time may sometimes make the mathematical programming unusable considering time constraints. Soft computing methods are easy to implement, but the solutions they provide, are not the most optimal and they also need long computation time [6].

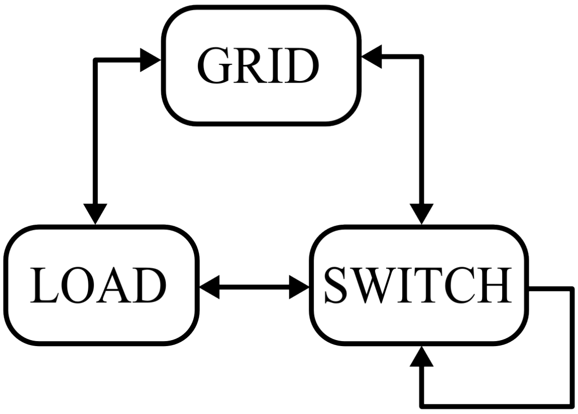

Fig. 1: Cooperation between autonomous agents.

2.2. Practical Implementation

We basically recognize two types of switching elements in medium voltage distribution networks according to their placement. There are breakers located in substations and remotely controlled switches and reclosers located in terrain [7].

Unlike recloser, the remotely controlled switch is able to break at most operating currents with specified overloads. The recloser is then capable of breaking fault currents as well. However, in compare with a breaker in substation the recloser contains simplified equipment for a measurement and protection. The most characteristic feature of recloser is the capability of reclosing sequence, which gave it its name. Reclosing sequence is an effective tool helping to reduce outage time for customers. There are a lot of faults lasting at most few seconds or fewer, so when the fault is gone, the line can be automatically switched on again into normal operating condition.

These switching elements can by default be either closed or opened, depending on basic operational scheme for a particular network. Fault occurrence may interrupt the feeding line supplying certain area. Using remote controlled switching elements is possible to isolate the fault from the rest of the network. The aim is to minimize the number of affected customers. Nevertheless, this activity often results in creating an area with no voltage but without fault. This area could be supplied through another switch that remains usually open during normal operation. However, there are some constraints to be met and calculation to be performed, what is nowadays dispatchers job.

Using an autonomous control system, some of the routines performed by dispatcher ought to be done by the limited intelligence of a switching element itself. Therefore switching elements, either in substations or in terrain, are the key components of autonomous control of medium voltage distribution network.

3. Agent and Multiagent System

An agent is a computer system that is situated in some environment, and that is capable of autonomous action in this environment in order to meet its delegated objectives [8]. Various authors propose many similar definitions, which emerge primary from a particular field of their research.

Characteristic feature of autonomous agent is the responsibility for given tasks. In the case of electrical power systems, it can be, for example, the control of power flow on certain line or voltage control in selected node. Agent has to be able to continually evaluate the activities he performs in order to revise future strategy if needed.

Although one agent is responsible only for given tasks, there may be many similar agents working in different parts of the environment and pursuing their own activities as well. Such a form of cooperation can, in the end, lead to the solution of a complex problem, which would require complicated analytical formulation and would take a long time to solve. The coalition of agents set in a certain environment and pursuing one common target is then called multiagent system (MAS), [8], [9].

Multiagent system doesnt use analytical algorithms to achieve its targets. Instead, communication is the most important instrument of multiagent systems operation. Autonomous agents send and receive messages and use provided information for composition of their following tasks.

3.1. Multiagent System for Power Restoration

Based on the analysis of the operation of medium voltage distribution networks in Slovakia, the multiagent system composed of three basic types of agents has been proposed. Key functions and roles of the agents have been designed concerning the ability of efficient power restoration [10].

1) Agent SWITCH

The most important type of agent in the process of power system restoration is SWITCH agent. This agent is bound with a remote controlled switching element. Some of the SWITCH agents activities are following:

- it locates faulted area through communication with other agents (Fig. 1),
- it sets its own role in restoration process,
- it estimates the load of faulted root line using own measurements and information from LOAD agents,
- it determines if there is enough power for restoration from healthy area,
- it makes final decision on switch/breaker manipulation in order to restore the power.

2) Agent GRID

It is very useful, when autonomous agents can rely only on the information available locally. However, sometimes there is a situation when only someone, who is holding knowledge about whole topology, can provide the information required. This is the main purpose of agent GRID.

GRID agent doesnt intervene in the process of power restoration. It stands by and provides topology related information on request. For example, it can be a query, if the power line is connected to any source at some remote terminal.

3) Agent LOAD

Concept of smart network brings a customer with installed intelligent device able to measure customers actual and cumulated consumption over a certain period. The device is connected to utilitys information network and implements bidirectional communication. It can send measured values on request, as well as to execute some control directives, e.g. load adjusting. Such a device is represented by LOAD type of agent. One of the most important tasks of LOAD agent is to help to estimate the load of outage area.

4. Restoration Process

Detection of a fault causes a certain breaker to trip. The SWITCH agent associated with the breaker sends a broadcast message *TrippingOccured* to all other agents. The message informs about the fault occurrence and about the agent, represented as sender that has broken the fault current.

When another SWITCH agent receives the *TrippingOccured* message, it creates a fault record and begins to evaluate its role in the upcoming restoration process. There are five possible roles:

- Tripping,
- Candidate,
- Assistant,
- Separator,
- Forwarder.

The role, an agent belongs to, depends on a physical location of the related switching element in the networks topology, its state and the type of area at the each of its terminals (Tab. 1). There are three types of areas, which can arise in the network after a fault has occurred:

- area with a voltage and without a fault–healthy,
- area without a voltage and without a fault–affected,
- area without a voltage and with a fault–faulted.

Generally, an agent having any of the roles uses the same principle of communication and message manipulation. The messages requesting available power or asking for restoration participants have a character of discovering. In case of request for power, the message travels from the agent at the edge of the affected area to its first neighbor in healthy area. Next, it is sent to the next neighbor in the direction from the affected area further to the healthy area and so on, until it reaches an agent able to provide some restoration power. This principle says that information travels stepwise from one agent to another. In other words, the coalition of agents cooperating on a single restoration problem is the smallest as possible. Then the problem is being solved primary in the area where it has originated.

The SWITCH agent evaluates voltages at both terminals of the related switching element and compares them with the values recorded before the arrival *TrippingOccured* message. Based on this evaluation, the type of area at each of the terminals is determined.

The SWITCH agent located between healthy and affected area has the role of **Candidate** (Tab. 1). It sends *ParticipantInfo* message to all of its neighboring agents located in the affected area, in order to create a list of agents co-operating on the same restoration task. In the same time it sends *PwrRequest* message to all of its neighbors from healthy area, in order to evaluate its restoration options.

Tab. 1: The rules according to which the role of the agent is assigned.

Role	Area 1	Area 2
Candidate	healthy	affected
Assistant	healthy	healthy
Separator	faulted	affected
Forwarder	affected	affected

An **Assistant** agent is located inside healthy area (Tab. 1). The function of **Assistant** agent is to process the request for power from another **Assistant** or **Candidate** agent. If a SWITCH agent receives the request for available power and sets its role as **Assistant**. Then it forwards the same *PwrRequest* to all neighboring agents from a side opposite to the sender of the request. If there are no neighbors at the side opposite to the sender, then it sends back the *PwrResponse* message with the value of available power equal to zero. If the switching element bound to the agent is connected to a power source, then the agent calculates the value of available power as a difference between a nominal power and an actual load of the source. If the switching element is opened, then the available power is labeled as offline, otherwise as online.

The **Assistant** agent waits until the number of *PwrResponse* messages is equal to the number of *PwrRequests* it has sent. Then the maximal online and offline values are selected. A single *PwrResponse* is then composed of the maximal online value, maximal offline value and their provider. This *PwrResponse* is then sent to the agent, which original *PwrRequest* came from.

An agent having the role of **Forwarder** works in a similar way, but inside of the affected area (Tab. 1). It collects the *ParticipantInfo* messages from its neighbors from both of the sides. When the *ParticipantInfo* messages from all the agents at single side are received, a combined response is created and sent to all the agents at the opposite side.

Candidate agents are the most important in the restoration process. They are located at the edge of affected and healthy area (Tab. 1). At first, **Candidate** agent evaluates its own available restoration power. Afterwards, it compares the own value with the values of other **Candidate** agents cooperating on the same restoration problem. Then the final decision, whether to switch on the given recloser (or remotely controlled switch) is made. If the own value of available power is the highest from all the others, then the order to switch on is given. If there are several **Assistant** agents on the way from **Candidate** agent to the actual power provider, then an activation message to the first **Assistant** in the healthy area is sent. This message informs it, it has to switch on and to forward the activation message as well.

5. Simulation of Multiagent System

In order to simulate the performance of multiagent system in the control of medium voltage distribution network, a software tool, named PSR (Power System Restoration) is being developed [10], [11]. It combines a physical simulation, graphical user interface and autonomous control in three different layers. The PSR tool is written in .NET framework, which provides a flexibility and advantage of rapid development.

5.1. MAS control system

The MAS control system consists of a specific number of autonomous agents according to the basic types defined in section 2. Each agent continuously monitors data, which it is bound to, e.g. a SWITCH agent monitors the voltages at both terminals of the related recloser. If the networks operating conditions are different from those expected by the agent, then it starts appropriate actions, especially the restoration process, with the aim to bring the operating conditions as close as possible to an acceptable state.

Every agent has a main runtime routine, which is common to all agent types. Each action the agent takes is included in this routine. It runs in a loop and in a separate thread, as long as simulation is active. It enables to simulate behavior of distributed system, where all agents are operating in parallel.

The activity of each agent is logged in a database in order to evaluate the sequence of the restoration process and to approximate the time required to solve the problem.

5.2. Physical simulation

The layer of physical simulation provides measurement input for all autonomous agents operating in the system. It uses the node voltage method for the calculation of power systems voltages, currents and power flows. This method was chosen because of its implementation simplicity and suitability provided for MAS control system. It should be noted, that there is no need for any dynamic process analysis. The MAS control system requires only the steady state values of the electrical parameters.

5.3. Graphical user interface

Graphical user interface of PSR tool consists of a read-only console and a SCADA window. The console is used for displaying all messages sent between autonomous agents. The SCADA window displays topology of the network and enables the user to manipulate with switching elements, to read operational electrical parameters and to manually set faults at desired locations.

6. Evaluation of MAS performance

In order to evaluate the performance of MAS, a model of typical medium voltage distribution network, was created (Fig. 2). It consists of 4 HV/MV transforming substations, 11 interconnected feeders, 7 reclosers and 33 loads. The PSR software was used to simulate a multiagent control of the given network. The main objective of autonomous agents was set to restore the power using a source with the lowest impact on its actual load. All the switching elements are in the configuration displayed on Fig. 2.

6.1. Fault situation

All the switching elements are in the configuration displayed on Fig. 2.

Tab. 2: Description of fault situation.

Faulted section	31-2
Feeder current before the fault	235,86 A
Load in the affected area	2362,03 kW
Tripping breaker	V31

Tab. 3: Actual loading and nominal power of operating transformers in supplying substations before the fault.

Name	Actual	Nominal
T1	125,83 A	700 A
T3	63,06 A	600 A
T5	126,39 A	630 A
T7	540,71 A	650 A

The faulted area is delimited by recloser R4 and breaker V31 (Fig. 2). After the breaker V31 has tripped the fault current, the restoration process begins (Tab. 4). The agent R4, bound to recloser R4, detects zero voltage on both of the terminals and zero current as well. Simultaneously, it receives a message from agent V31 informing that tripping has occurred on breaker V31. Based on these facts agent R4 sets its role as **Separator** and changes the state of the recloser to open and thereby separates the faulted area from the rest of the network. The area affected by the fault is delimited by reclosers R4 and R1, and breakers V22 a V11. There are three possibilities to restore the power in the affected area: from substation STA2 through breaker V22, from substation STA1 through breaker V11 or from substation STA4 through recloser R1 and breaker V41.

Tab. 4: Simplified and shortened log of the restoration process.

Time	Agent	Action
12:45:07,190	V31	Tripping
12:45:07,199	R4	Switch OFF separates faulted area
12:45:07,414	R1	Starts Candidate action
12:45:07,441	V22	Starts Candidate action
12:45:07,452	R2	Starts Forwarder action
12:45:07,461	V41	Starts as Assistant receives PwrRequest
12:45:07,462	V11	Starts Candidate action
12:45:07,487	T6	Sends PwrResponse to agent V41
12:45:07,502	T1	Sends PwrResponse to agent V11
12:45:07,510	T3	Sends PwrResponse to agent V22
12:45:07,541	R1	Available power value evaluated
12:45:07,568	V11	Available power value evaluated
12:45:07,570	V22	Available power value evaluated
12:45:07,606	V11	The highest restoration power found
12:45:07,618	V11	Is able to cover all the load of the affected area
12:45:07,529	V11	Order to switch on
12:45:07,629	V11	Power in the affected area restored

The agent R4 informs agents R1, R2 and V22, that a fault has occurred and sends them the value of the power flowing through recloser R4 measured before the fault tripping, which also represents an actual load inside the affected area. This assumption can be made according to a fact, that there are usually no circular power flows in distribution networks and each load is supplied from single feeder and single substation. The agent R2 has the role of **Forwarder**, because it is inside the affected area (Tab. 1). It forwards the messages enabling **Candidate** agents, located at the edges of the affected area, to find each other. It is important for every **Candidate** agent to create the list of restoration participants, because it must compare its own restoration power with the other candidates. The result of the comparison is essential for the agents decision whether to continue in the restoration process or not. The agents having the role of **Candidate** are R1, V22 and V11. **Candidate** agents sent requests for available power towards the substations STA1, STA2 and STA4. In case of agent R1, request for available power travels to agent T5 in substation STA4 through agent V41 having the role of **Assistant**.

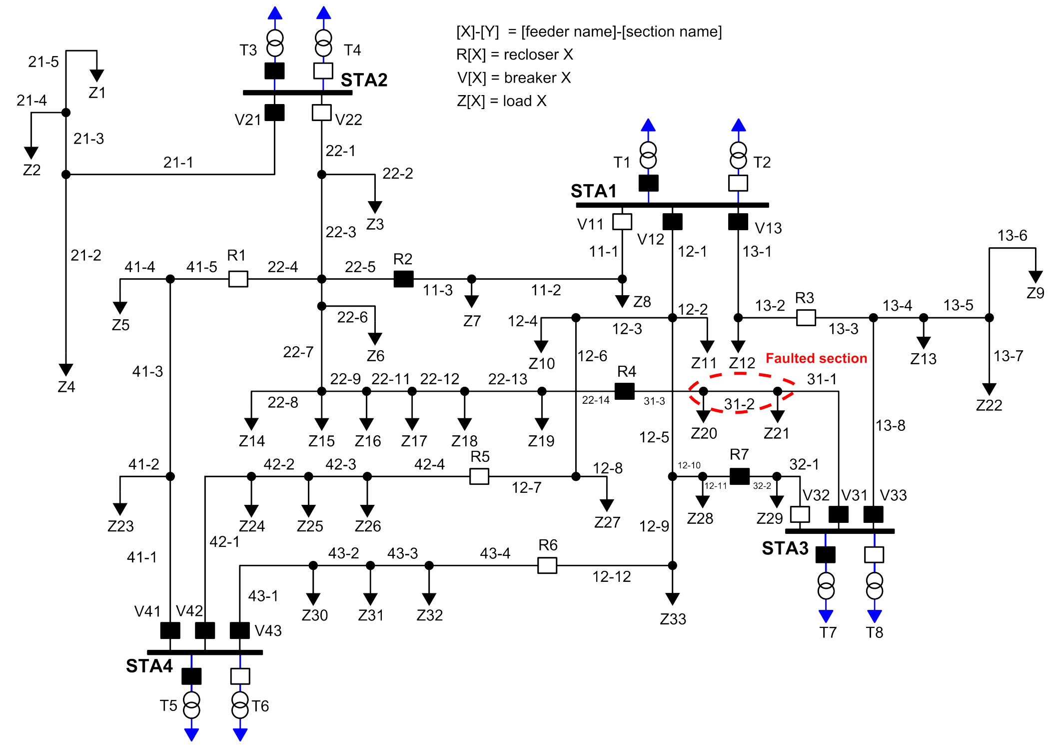

Fig. 2: Model network used for MAS performance analysis.

The agents able to provide online power are T1, T3 and T5. The best provider of restoration power, in terms of previously given criteria, is agent T1, because it has the highest difference between nominal and actual load (Tab. 3). The switching sequence of the restoration process begins with the tripping of breaker V31 (Tab. 5). The recloser R4 then switches off and thereby separates the faulted area from the rest of the network. The **Candidate** with the highest restoration power available is agent V11. It switches on, and thereby restores the power in the affected area.

Tab. 5: Switching sequence of fault event and its restoration.

Name	State
V31	OFF
R4	OFF
V11	ON

An overall length of simulated restoration process, from fault current tripping until the restoration of the affected area, was 469 ms (Tab. 4). However, the length of restoration is expected to be longer in real operation because of communication delays of basically random length.

7. Conclusion

In this paper, we have presented a multiagent approach to power system restoration. The proposed multiagent system consists of a number of SWITCH agents and a single GRID agent. GRID agent provides topology related information on request. Each SWITCH agent controls a single recloser or remote controlled switch. An agent at the edge of healthy and fault affected area communicates with its neighbors in the healthy area in order to obtain the value of available power. If the agents own available power is the highest in compare with the values from other participants, then it orders to switch on its bound switching element and thereby to restore the power.

Presented simulation of the restoration process controlled by multiagent system is one of the simplest cases of fault situations. It has been chosen primary for initial development and debugging of PSR software. However, it proves, that MAS technology is especially suitable for the control of power distribution networks and PSR software is able to test MAS control algorithms and to provide a rough estimation of the overall process length. Control methodology, as well as PSR, software is still in development and is going to be used for simulation of more complex fault situations in the future.

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