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Increasing power supply reliability of the distributed generation network

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Abstract

Today, there is an active development of distributed generation networks, but this development is undoubtedly associated with reliability problems. Newly constructed microgrid networks should have the ability of automatic restoration process after emergencies to short the downtime of load. For that purpose in this paper, the control model of the inverter with the automatic restoration algorithm was developed. All the algorithms were designed and verified on the RTDS simulator.

Keywords— distributed generation, virtual inertia, machine learning, power restoration.

I. INTRODUCTION

The worldwide electricity demand is increasing every year, so energy companies are actively developing projects to introduce new power capacity to provide the necessary power generation. Since in most cases the building of large energy centers is capital intensive, the construction of distributed generation facilities is being actively implemented, with faster development and lower capital costs.

The main feature of small-scale renewable energy sources, in addition to their possible intermittent nature of electricity generation, as well as a gas turbine or diesel, is a general decline in the system inertia. System inertia is one of the most important indicators that determine whether it is possible to maintain both static and dynamic stability of the energy system. The lower the inertia value, the more likely it is to be deactivated with significant perturbations.

The lower system inertia can lead to another more important problem of complex systems, it is reliability indexes because more possible outages increase equipment downtime whereas the duration of downtime depends on the location of the microgrid or accessibility of the maintenance brigade.

To increase the reliability there are two ways: decreasing the electricity absence time by implementing a restoration algorithm or decreasing the outage frequency by utilization modern more reliable technology. The latter is associated with the new microgrids building so the former is more likely can be realized in the existent microgrids.

This paper is structured as follows. In Section II the control strategy of the inverter is given Section III describes the developed restoration algorithm. Section IV introduces the method of short circuit recognition with the use of a neural network. Simulation and experimental results are presented in Section V.

II.INVERTER CONTROL STRATEGY DESIGN

The most common principle of control power electronic device utilizes the dq-representation of currents and voltages of the grid [1]. It is necessary for precise enhanced regulation because control of constant values is easier than control of alternated sinusoidal values, which are currents and voltages.

A.Grid-connected operation of an inverter

The reference model of typical inverter control and connection to the main grid is illustrated in Fig.1.Control of output power is regulated by the following equations according to dq-transformation:

$$P(t) = \frac{3}{2}\left[v_d(t)i_d(t) + v_q(t)i_q(t)\right] \qquad (1)$$

$$Q(t) = \frac{3}{2}\left[-v_d(t)i_q(t) + v_q(t)i_d(t)\right] \qquad (2)$$

To calculate the reference current based on the power settings, based on (1) and (2) at p = ω0 t + θ, where ω0 – grid frequency, in the steady-state we obtain:

$$i_{dref}(t) = \frac{2}{3V_{sd}} P_{sref}(t) \qquad (3)$$

$$i_{dref}(t) = \frac{2}{3V_{sd}} Q_{sref}(t) \qquad (4)$$

In general, the equations of the electrical system in Fig. 1 can be expressed through (5), where L – induction of the LC-filter, R – resistance of LC-filter, ron – resistance of an opened power electronic switch.

$$L\frac{d\vec{i}}{dt} = -(R + r_{on})\vec{i} + \vec{V}_t - \vec{V}_s \qquad (5)$$

Applying to (5) the dq-transformation we obtain:

$$L\frac{di_d}{dt} = L\omega_0 i_q - (R + r_{on})i_d + V_{td} - V_{sd} \qquad (6)$$

$$L\frac{di_q}{dt} = -L\omega_0 i_d - (R + r_{on})i_d + V_{tq} - V_{sq} \qquad (7)$$

Taking into account (6), (7) the following control schema is used to control the output current of the inverter, where Kd, Kq are PI-controllers, md, mq – modulating signals.

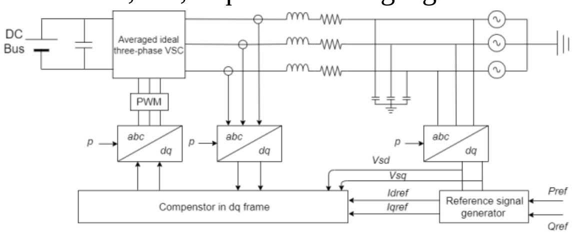

Figure 1. Reference model of inverter control.

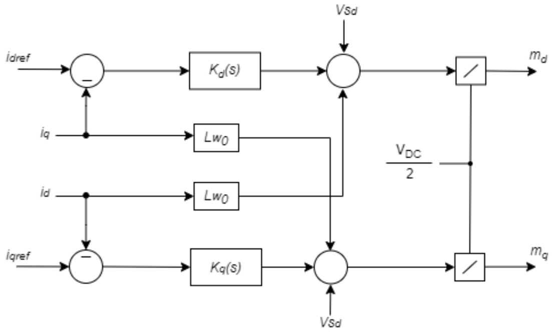

Figure 2. The output circuit of the VSC control system, to control the output power

B.Autonomous operation of an inverter

If for any reason the network voltage is missing, the inverter must set and maintain the required voltage level with a certain frequency. For this purpose, an additional voltage control unit should be added to the inverter control diagram in Fig.2.

For the capacitor of the output LC-filter, we can write the following equation of current change, where *i* – inverter output current, i_L – current after LC-filter, V_S: - network voltage, C_f - LC-filter capacitance.

$$C_f\frac{d\vec{V}_s}{dt} = \vec{i} - \vec{i}_L \qquad (8)$$

Applying to (8) the *dq*-transformation we obtain:

$$C_f\frac{dV_{sd}}{dt} = C_f(\omega V_{sq}) + i_d - i_{Ld} \qquad (9)$$

$$C_f\frac{dV_{sq}}{dt} = -C_f(\omega V_{sd}) + i_q - i_{Lq} \qquad (10)$$

The left components of (9), (10) are a variation of the voltage on the capacitor that needs to be controlled, i.e., a new control signal must be introduced:

$$u = C_f\frac{dV_s}{dt} \qquad (11)$$

Then, taking into account the (11), convert (12), (13) to calculate the output current:

$$i_{dref} = u_d - C_f(\omega V_{sq}) + i_{Ld} \qquad (6)$$

$$i_{qref} = u_q + C_f(\omega V_{sd}) + i_{Lq} \qquad (7)$$

The result is an equation of a voltage regulator whose output signals have to be applied to the current regulator. The resulting control schema is shown in Fig.3, where *Kd, Kq* are *PI*-controllers, *Vdref, Vqref* – desired voltages, *ILd, ILq* – line currents.

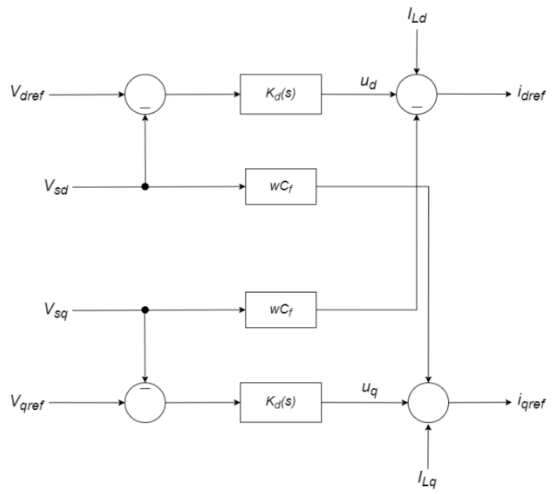

Figure 3. The inner circuit of the VSC control system, to control the output voltage.

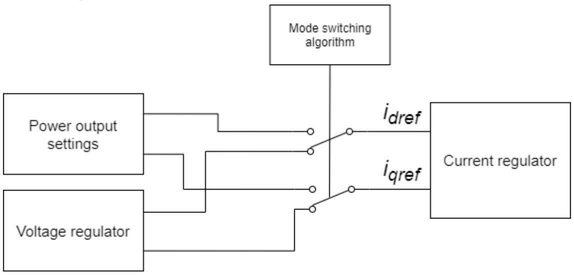

Figure 4. Mode control schema of the inverter

Therefore, taking into account the current controller and the voltage controller, the following control system design is developed shown in Fig. 4, which can operate both in parallel to the network and in stand-alone mode.

III.RESTORATION ALGORITHM

In accordance with the standard [2], during an emergency, the network can be isolated from the main grid for static and dynamic stability purposes. However, when switching from network mode to isolated mode, power generating units can be disabled by their protection algorithms. In addition, control circuits may extend beyond their narrow stability zones, which can also lead to a loss of power supply. As a result, some consumers will suffer from a power outage. In order to restore the power supply as soon as possible, it is necessary to develop an algorithm for restoring electricity.

There are various approaches to implementing such algorithms that depend on the availability of a communication channel between all devices, but this may not be possible in remote areas. Thus, the developed algorithm allows the system to perform a correct recovery without using additional communication channels.

After a certain event occurs, namely: a short circuit in the network, a shift of the network to an isolated mode of operation, a sharp power surge, etc., the load switches and the inverter are turned off. Then the inverters are switched on alternately with a random time delay in the voltage source mode, while each inverter at the time of switching on monitors the presence of a voltage source for switching on as a current source mode. In turn, the load must be switching on with a time delay in accordance with its category. As a result, the total recovery time may be significantly less than it would have been if you had enabled it manually.

The recovery logic is based on the correct closing of all opened breakers and switching any inverters to voltage source mode. There are three types of active devices that must be entered for the recovery algorithm to work properly

A.Sectioning switch restoration logic

This type of switch is primarily used to form a network, therefore, after a short circuit, the sectioning switches must be switched on first to create maximum network connectivity, therefore, in the case of a short circuit, it is necessary that other devices are tuned from the activation time of the sectioning switches. As a result, the described algorithm is shown in Fig. 5.

B.Load switch restoration logic

As a result of the island mode of the network, upon loss of the voltage source, the load switches check for loss of voltage or change in sinusoidal voltage and disconnect. Further, when voltage is applied, the start time is maintained at the priority level of the consumer categories, and the start time is tuned from the average activation time of at least one inverter.

The need to turn off the load switches is due to the possibility of re-disconnecting the load during the supply of voltage to the network. This is due to the fact that while the inverter is turned on in the voltage source mode, it will not be able to power all consumers until the other inverters are turned on in the current source mode.

As a result, the algorithm of the operation of load switches is shown in Fig. 6.

As you can see, the load activation algorithm is fully confident that after restarting the system will fully restore power with the help of autonomous inverters

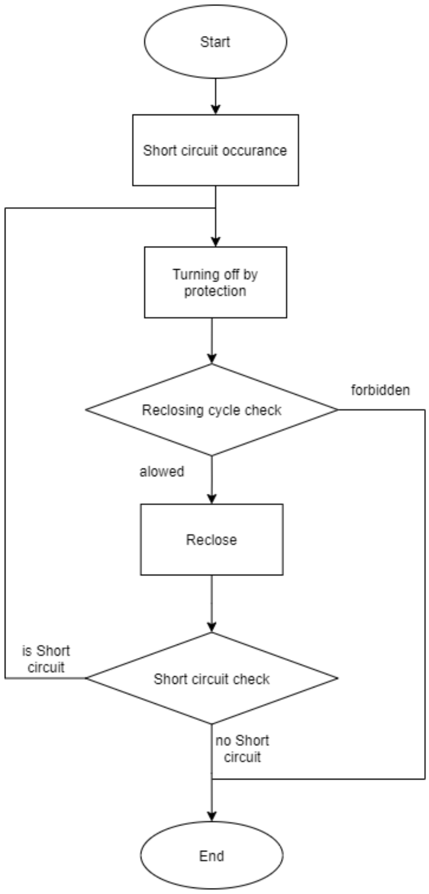

Figure 5. Sectioning switch restoration logic

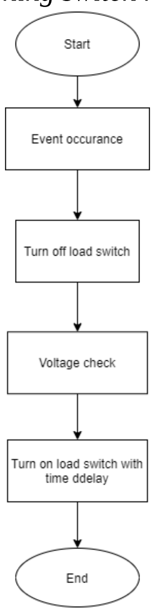

Figure 6. Load switch restoration logic

C. Inverter restoration logic

The most important part of the load supply in an isolated network is an inverter that can operate autonomously, so the complete restoration of power in the microgrid will depend on their correct and coordinated operation. The main problem in the isolated mode of the network is the absence of a voltage source; at a time there can be only one such source in the network because it is impossible to coordinate the inverters of voltage sources together in the absence of fast communication channels. This can be overcome by sequentially turning on the inverters after they are turned off due to the islanding. In this case, each inverter is ready to act as a voltage source after switching off. If during startup the inverter notices the appearance of voltage in the grid, it means that either synchronization with the main grid has occurred, or there is already a voltage source in the grid and the inverter should start working in the current source mode. In addition, the logic of the inverter implies monitoring the cause of its shutdown. If the cause is a short circuit, the inverter turns on with a longer delay in order to turn off the sectional switches and, after switching on, control the occurrence of a repeated short circuit.

Various approaches can be used to determine the cause of the inverter shutdown. As part of this work, an unconventional approach using machine learning technologies has been developed, which is described below (Fig. 7).

IV. THE SHORT CIRCUIT RECOGNITION ALGORITHM

Every year, the technologies for the production of embedded system microcontrollers are improved, which, firstly, leads to an increase in computing power, and secondly, to a decrease in the cost of their production. In addition, one of the main trends in modern technology is machine learning, which is why manufacturers are also trying to release their products designed for machine learning tasks. As a result, today there are quite powerful and affordable system-on-a-chip models that can be built into the end device to solve machine learning problems.

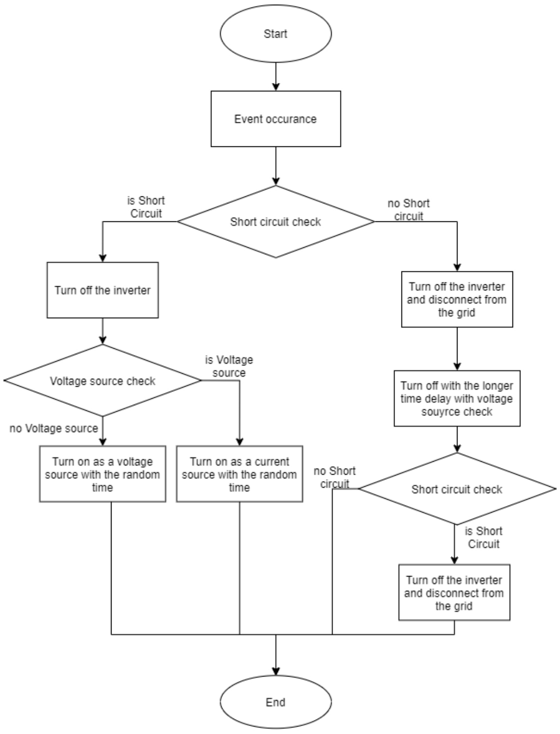

Figure 7. Inverter restoration logic.

To determine the cause of the loss of voltage in the network for the correct operation of the recovery algorithm, a machine learning model was developed, the training of which was carried out on data obtained from the power-hardware-in-the-loop (PHIL) model.

Convolutional neural network

Neural networks allow you to build high-quality models that can generalize information from input data and make the right decisions. Therefore, for example, a convolutional network, because of its architecture, looks for certain patterns in local areas of input data and then can define them in completely new data. For the convolutional neural network to work correctly, it is necessary to prepare the signal data. The recorded waveforms of currents and voltages at the point of connection of the inverter to the network are used as training data. All data is divided into time windows of 6 channels (3 currents and 3 voltages), 40 ms each in the sample (Fig.8).

Based on the training results, the quality of the algorithms was studied on a test sample, which is 30% of the data. For clarity, the operation of the algorithm was visualized using the confusion matrix (Fig. 9).

From the confusion matrix, it can be seen that the model did an excellent job of classifying the test waveforms without making a single mistake. However, it should be noted that this is the only analysis of the test data. The behavior of the developed algorithm with different real data requires further study.

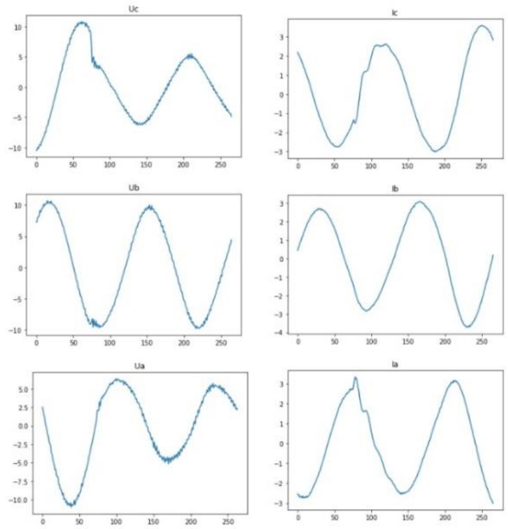

Figure 8. Training data. Left-voltage channels, right-current channels

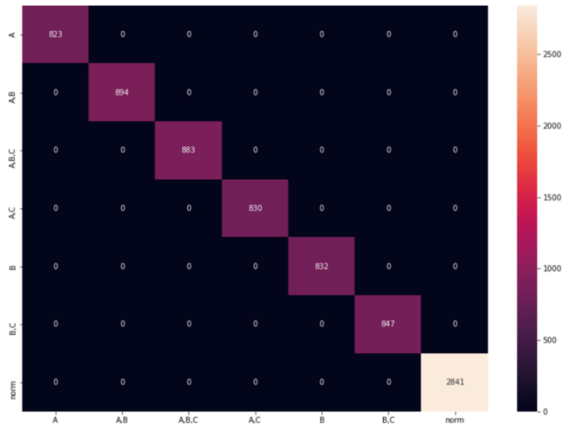

Figure 9. Confusion matrix

V.SIMULATION

The basic architecture of a microgrid is typically a radial AC system with some point of common coupling (POC) connection to the mains. The main elements of such a network are energy storage systems, distributed sources of electricity, electricity consumers, and a distribution network.

In this paper, the task of investigating the behavior of individual energy sources is not set, but the possibility of controlling inverter converters is considered, therefore, we assume that on the DC side of all inverter converters there is any DC voltage source, when the voltage changes, we will be able to simulate the power limits that this conditional energy source is capable of producing. As a result, Fig. 10 shows a diagram of the resulting microgrid network model under study. The microgrid contains 3 inverters, 18 loads of 20 kW each, the main grid of 10,5 kV.

To simulate the developed algorithms and control systems, the software and hardware complex Real-Time Digital Simulator is used in this work.

The RTDS package is a specialized complex designed to study electric power modes and simulate electromagnetic and electromechanical transients with a standard calculation step of 50 microseconds. The package works in hard real-time mode, that is, all computing processes are guaranteed to be performed faster than the next step of the calculation is completed, which allows you to connect real devices to it to check their operability.

In this work, the RTDS is used to conduct studies of electromagnetic and electromechanical transients in the AC network with the possibility of modeling modes, the creation of which in real conditions is associated with a danger to human life or with high costs in the study of the operation of the power system when its configuration changes.

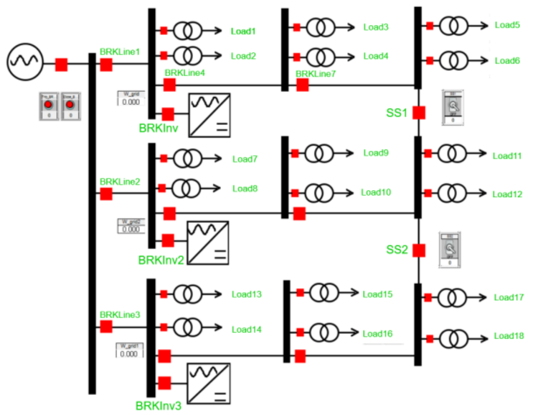

Figure 10. Microgrid model

A. Islanding simulation

To check the operability of the recovery algorithm, the transition of the microgrid network to the island mode of operation with the disconnection of the head switch of the network was simulated. As a result, the algorithm worked out clearly, turning off the entire load, as well as the inverters, and then the network was switched on correctly. Figure 11 shows a diagram of the process of switching on all loads, as well as inverters

The calculation of the average turn-on time of the entire load and inverters after switching to island mode was carried out, the results of which are shown in Fig. 12, 13

Based on the diagrams, the average recovery time of switching on the first inverter is 0.05815 s, and the time to fully restore power to the entire load is 0.322225 s, which takes much less time if switching on occurred in manual mode. The SAIDI reliability index as a result of the simulation is 0.45. Such a short recovery time directly affects the reliability indicators (SAIDI, ENS, AENS)

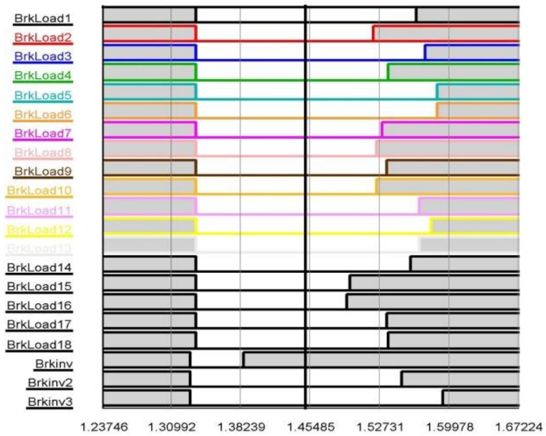

Figure 11. Restoration process after islanding.

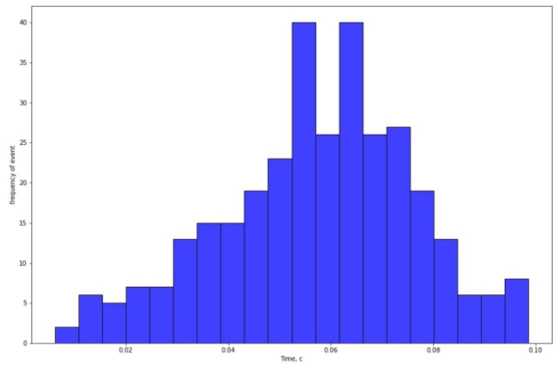

Figure 12. Load restoration time distribution

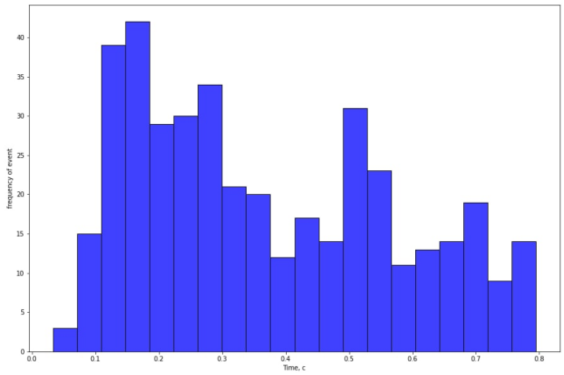

Figure 13. Inverter switch-on time distribution

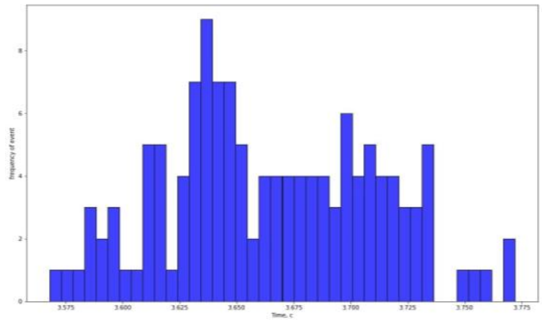

Figure 14. Load restoration time distribution after short circuit

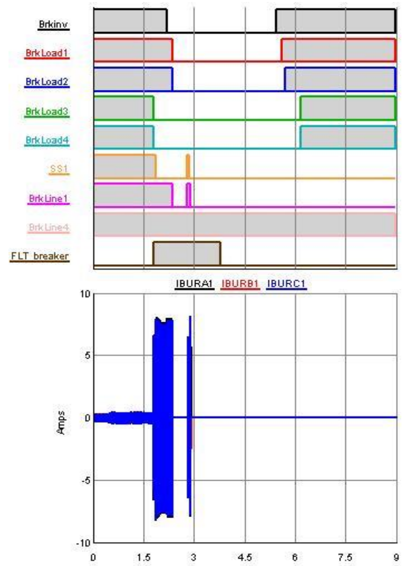

Figure 15. Restoration diagram after sustained short circuit.

B. Short circuit simulation

In the event of a short circuit on the feeder, the sectional switches must be tripped by the protection to localize the short circuit. Further, after disconnection, these switches are automatically turned on again and, if successful, the power to the local section is restored, while the inverters and the load will be connected in parallel with the main network. If the reclosing fails, but the short circuit is cleared by itself, the inverter and the load are switched on in local island mode. In the event of a stable short circuit, the inverters will turn off after restarting, and the subsequent elimination of the accident goes to the repair team. Further in the text, the graphs of restoring loads and inverters are presented in two cases. In the first case, the short circuit is unstable (less than 0.5 s), and automatic reclosing effectively restores power supply to the local section (Fig. 15), in the second case, the short circuit is stable, but less than 2 s and the network goes into island mode (fig. 16)

The average time of the load switching on after automatic power restoration was calculated, the results of which are shown in Fig. 14. Based on the obtained distribution, the average time to complete power recovery of the entire load in the local zone is 3.637 s, which is significantly less time if the circuit breaker was closed in manual mode. The SAIDI reliability index as a result of the simulation is 3.67.

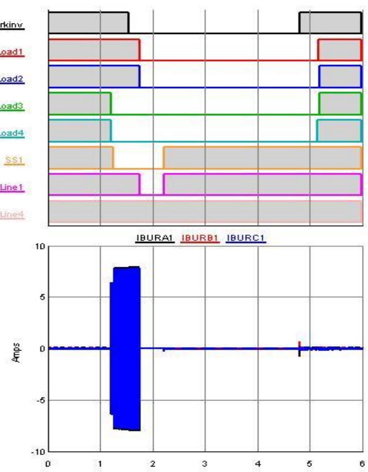

Figure 16. Restoration diagram after cleared short circuit

CONCLUSION

This paper introduces the method of power supply restoration after an emergency in a microgrid network. Because of the coordinated operation of neural network and restoration algorithms, the developed method is capable of effectively restore power supply in different situations in a simple islanding transition and in a more complex short circuit event when there is a local islanding mode. In addition, an important feature of the developed method is the absence of additional communication lines that make the whole microgrid less expensive.

Simulation of the algorithm shows that the time for restoration process takes as little time as possible and the overall load recovery is 0.2 s. Such small time bring to a smaller reliability index – SAIDI which makes the whole network more reliably

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