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An experimental study of passive methods for islanding detection and protection system of the inverter operation

***Abstract**. In this paper, we analyze the method of passive over/under voltage for protection and distribution of PV systems connected to the utility grid. The method in question is analyzed by non-detection area and based on the possibility of degradation of output power quality, which is a known weak point of this method. The analysis focuses on the worst case detection when the energy produced by the photovoltaic system is the same energy that takes the load when there is no change to the parameters at the common point of connection to the utility grid. An algorithm is proposed to solve the problem of the creation of the so-called islanding of generators connected to the grid. Simulations were conducted with Matlab Simulink software.*

Streszczenie.** W artykule analizowano pasywną metodę detekcji pracy wyspowej z wykorzystaniem zabezpieczenia nad/pod napięciowego w przypadku systemu dystrybucyjnego zawierającego system PV. Analizowano obszary nie-wykrywania zagrożeń. Skoncentrowano się na najgorszym przypadku, w którym energia wytwarzana przez system fotowoltaiczny jest w całości pobierana przez odbiór, podczas gdy nie występują zmiany parametrów w punkcie wspólnego przyłączenia do sieci elektroenergetycznej. Przedstawiony algorytm rozwiązuje problem kryteriów dla detekcji pracy wyspowej jednostek wytwórczych przyłączonych do systemu elektroenergetycznego.* ***Eksperymentalna analiza pasywnej metody wykrywania pracy wyspowej i zabezpieczenia falownika

Keywords: photovoltaic module, utility grid, islanding detection, passive methods.
Słowa kluczowe: systemy fotowoltaiczne, system elektroenergetyczny, detekcja pracy wyspowej, metody pasywne

Introduction

The distributed generation of electricity is an option that is being considered seriously around the world, especially in countries where the centralized power generation system is very old and causes large environmental pollution. Distributed generation, as defined by Karlsson [1] is "…an electrical power generation source connected directly to the distribution grid or on the customer side of the meter". One of the main problems encountered in distributed generation is the possible formation of isolation conditions (areas called the island) that can continue to work normally even if the electrical grid is disconnected [2]. For applications without detection and correction, it is better to combine more methods for detection of islanding detection based on other work processes [3]. The distribution generation is considered to be in unity power factor operation [4]. This unity power factor condition combined with passive parameters of parallel RLC load and frequency, as given in (1)-(4), is considered the worst case for islanding detection when the active power of load matches to output power of distribution generation.

1. The power generated by DG should match the RLC load power, $D_P = 0$ and $D_Q = 0$.
2. A resonant frequency of the RLC load is the same as grid line frequency (f = 50Hz).
3. The quality factor Q_f of RLC load is set to be 2.5. The quality factor is defined as that the reactive power stored in L or C is at times the active power consumed in R.

Load definition can be represented as

$$f = \frac{1}{2\pi\sqrt{LC}} \tag{1}$$

$$R = \frac{V^2}{P} \tag{2}$$

$$L = \frac{V^2}{2\pi f Q_f P} \tag{3}$$

$$C = \frac{Q_f P}{2\pi f V^2} \tag{4}$$

where: R - effective load resistance [W], L - effective load inductance [H], C - effective load capacitance [F], P – active power [W], Qf – quality factor, f – grid frequency [Hz].

The values of frequency and magnitude of the voltage at the point of common coupling (PCC) after grid disconnection (islanding condition) depend heavily on the local load characteristic. Furthermore, Bower [5] and Stevens [6] also mention why islanding is undesirable. The frequency of the system when it is under islanding, *ωi,* is the function of the invertor active power P_{PV}, and reactive power Q_{PV}, and resonant load frequency $(\frac{1}{\sqrt{LC}})$.

$$\omega_i \approx \frac{1}{\sqrt{LC}}\left(1+\frac{Q_{PV}}{2qP_{PV}}\right) \tag{5}$$

The inverter terminal voltage Vi at the disconnection time of the utility grid [7] is the function of the active power ratio of the PV inverter and the load as described in equation (6),

$$V_i = \sqrt{\left(\frac{P_{PV}}{P_{Load}}\right)}V_n \tag{6}$$

where *Vn* is the nominal voltage of the system.

From [5] it can be noted, at the instant when the island is formed (utility is disconnected), the system behavior depends on ΔP and ΔQ as follows:

(ΔP>0): The inverter terminal voltage will increase above the nominal system voltage.

(ΔP<0): The inverter terminal voltage will decrease below the nominal system voltage.

(ΔQ>0): The frequency will increase until reactive power supplied by the capacitor C balances with that consumed by the inductor L.

(ΔQ<0): The frequency will decrease below nominal system frequency.

The power mismatches are large (Δ*P*> ±20% or ΔQ > ± 5%), causing the voltage or frequency to go out of the nominal range for detecting islanding. But if the mismatch is quite small, with the voltage and frequency within the nominal range, detection of islanding becomes impossible, causing thus a large Non-Detection Zone (NDZ). Small ΔP results in an insufficient change in voltage amplitude and small ΔQ results in an inadequate change in frequency to effectively disconnect the PV and prevent islanding. The probability of small values of ΔP and ΔQ for the NDZ is significant, and protection devices cannot detect an island reliably. In general, over/under voltage devices alone are considered to be insufficient as anti-islanding protections. It is possible to calculate the NDZ from the mismatches of active and reactive power and to set the threshold values for voltage amplitude and frequency.

Passive detection methods have a large non-detection zone (NDZ) and that is not a significant anti-islanding protection. Two main system parameters frequency and the voltage at the point of common coupling (to assign the size of NDZ) can change their values depending on a variable load connected to the grid. If an inverter has the capability of over/under voltage protection and over/under frequency protection, we say it has the basic islanding detection capability. Active detection methods should be also used to decrease the size of NDZ. But the main disadvantage of active methods is the injecting of a disturbance signal into the grid. For a faultless and correct use is better to combine more islanding detection methods based on another working process.

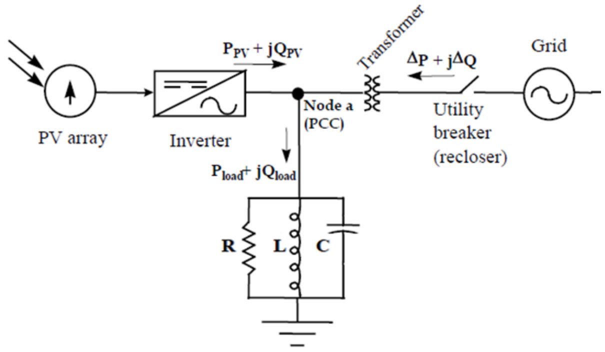

Fig.1. PV system/utility feeder configuration showing power flows [10]

Over/under voltage islanding detection passive methods

Passive islanding detection methods rely on the measurement of system parameters (such as the variation in the voltage, frequency, harmonic distortion or the power) that cause the inverter to control/modify the output power to meet specific conditions during islanding mode of operation [8]. The parameters vary greatly at the PCC when the system is islanded. The difference between a normal grid-connected condition and an islanding condition is based on the threshold setting of the system parameters. In general, passive detection techniques are fast and create little disturbance in the system. However, they suffer from large non-detection zones (NDZ) which could fail the islanding detection [9].When the switch is closed, and the utility is connected (Fig. 1), real and reactive power PPV + jQ_{PV} flows from the PV inverter to the node, and power P_{load} + jQ_{load} flows from the node to the load. Summing power flows at node

(7) $$\Delta P = P_{load} - P_{PV}$$

(8) $$\Delta Q = Q_{load} - Q_{PV}$$

We obtain the real and reactive power flowing into node from the utility. If the PV inverter operates with a unity power factor (that is, the PV inverter output current is in phase with the voltage at the node), then $Q_{PV} = 0$ and $\Delta Q = Q_{load}$. For most islanding detection methods, it is some RLC load that causes the most difficulty in detection. General nonlinear loads such as harmonic-producing loads or constant-power loads do not exhibit as much difficulty in islanding prevention. RLC loads with a high q (quality factor) are most problematic for islanding detection. The quality factor can be expressed as:

(9) $$Q_f = R\sqrt{\frac{C}{L}}$$

Parameters R, L, and C give the relative amounts of energy storage and energy dissipation. Real and reactive power of the load can be expressed as:

(10) $$P_{Load} = \frac{V_{PV}^2}{R}$$

(11) $$Q_{Load} = V_{PV}^2\left(\frac{1}{\omega L} - \omega C\right)$$

Real and reactive power supplied by the PV Inverter can be expressed as:

(12) $$P_{PV} = V_{PV} I_{PV} Cos\theta ,$$

(13) $$Q_{PV} = V_{PV} I_{PV} Sin\theta ,$$

where V_{PV} and I_{PV} are *RMS* values and *Cosθ* is the power factor.

Equations (10) and (11) describe the active and reactive power consumed by the RLC load. If the active power demand of the load and active power production of PV system are not the same as the instant when the breaker opens, then the voltage at PCC must decrease or increase until PPV =P_{load}. Similarly, if the reactive load power demand and reactive power production are not matched at the time when the grid is disconnected. The frequency *w* at PCC must change until QPV = Ql_{oad}. The mechanism, by which this happens, is that the PV inverter will seek a frequency at which the current-voltage phase angle of the load equals that of the PV system. Such voltage and frequency changes can be detected by over/under voltage. Difficulties appear when a load demand and PV generation are close. Then frequency or voltage changes can be insufficient to enable detection by PV inverter. It is the reason why it is necessary to develop islanding techniques which can detect these cases when the powers of PV and load are closely matched. It is the aim of all islanding detection methods to reduce the non-detection zone near to zero.

System description

In order evaluate the performance of such techniques, a PV system, with capacity 3.9 kWp, was installed on the roof of Laboratory buildings at the Faculty of Electrical and Computer Engineering in Pristina, Kosovo, and connected to the grid system. This system consists of two types of photovoltaic modules [11], monocrystalline and polycrystalline, batteries, inverter, battery chargers and devices for measurement and monitoring. The grid-connected systems consist of 18 modules, with an active surface area of 26.26 m2. Specifically, the system comprises PolySol 240 VM (IBC Solar, STC Power 240 Wp, module efficiency 14.7%) polycrystalline silicon modules, and 9 MonoSol 195 DS (IBC Solar, STC Power 195 Wp, module efficiency 15.3%) monocrystalline silicon modules. The PV modules are arranged in 2 branches with nine modules each connected to a Sunny Boy SB 2000 inverter, irradiance and temperature measurement instrumentation and data logging systems (Sunny Sensorbox and Sunny WebBox).The roof is approximately 8 m high, and the modules were fixed mounted at an angle of 45^0, facing south. Such a tilt angle was chosen to maximize yearly energy production, taking into account the geographical position of Pristina. The grid-connected PV system was monitored to assess the performance of this system in the local climate conditions. The data acquisition systems consist of a Sunny Boy 2000 inverter, Sunny SensorBox, and Sunny WebBox. Sunny SensorBox was used to measure in-plane total solar radiation on the PV modules. There are also additional sensors for measuring ambient temperature and module temperature at the back of one module and wind speed. The Sunny SensorBox and inverters were connected to the Sunny WebBox. Data recorded on 15 min intervals is collected by WebBox extracted via SD card and read directly into a computer. Inverters without transformers should operate with photovoltaic modules with class II protection by IEC 61730, and amplification class A and these modules must be compatible with this product. Photovoltaic PV modules should use high grounding levels if the coupling capacity does not exceed 1.4μF. The inverter is equipped with Bluetooth, which can communicate with other devices or can be remotely controlled, and is also equipped with the SMA standard that is a basic type of Ethernet communication standard. This enables optimization of inverter work for 10-100 Mbit speed data transmission from PV system to Sunny Explorer inverter software. There are two inverters connected to each branch, of photovoltaic panels, so there are two independent systems (one for the monocrystalline modules and the other for the polycrystalline modules). The schematic block circuit of the PV system is shown Figure 2.

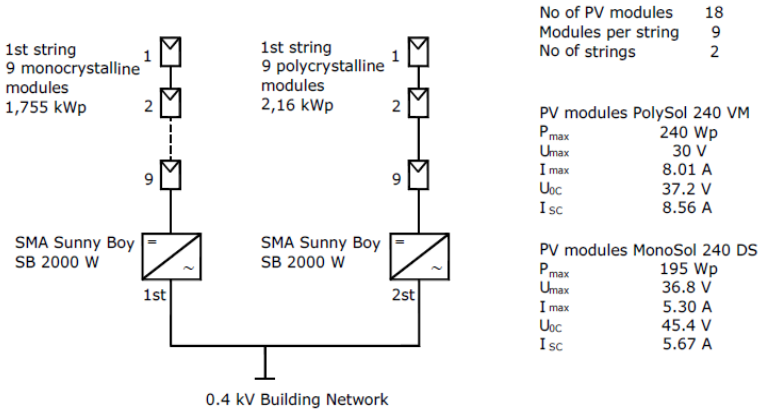

Fig.2. Schematic block circuit diagram of the PV system [12]

Sunny Boy is a PV inverter without a transformer that converts the DC power supply to a suitable AC power supply and transmits it to the service network [13]. From the collected measurements it is noted that, for the same radiation and at the same time, solar panels produced from monocrystalline silicon produce 171 W power, while the solar panels produced by polycrystalline silicon produce 218 W power.

So, the solar panels produced by polycrystalline silica, under the same conditions, yield 47 watts more power than monocrystalline silicon. In the case of Fig. 1, the PV inverter is also connected to the service network and with the battery, and at the same time is delivering power to both. The system works in this way: when the battery is charged over 30%, the inverter automatically supplies only the service network, while, when the battery falls below 30% with the supply, the inverter automatically supplies only the battery. Our observations show that passive methods, such as the over/under voltage protection method, are very effective detecting isolation circumstances, and do not impair the output power quality. However, they fail to detect the isolation circumstances in the case when the energy gained by the PV system is equal to the energy it receives from the load, i.e. when $P_{DC} = P_{Load}$. Therefore, when isolation circumstances occur in such conditions (i.e., in the event of a failure of the utility grid), the protective relay cannot detect the change of the set threshold parameters in the PCC. This leads to the conclusion that the over/under voltage protection method should be enhanced with an additional relay which functions as the inverters interrupter from the utility grid whenever $P_{DC} = P_{Load}$.

In this way, this inverter disconnects the system from the utility grid at the time the inverter produces as much energy as it receives the RLC load and is used as a preventive. Also, there are no unwanted effects either in the system or on the load, and during this time there is no reason for the inverter to be connected to the utility grid.

Table 1. The data obtained (the best case from many measurements made) of the PV system placed in the FECE laboratory

Time	**Fac**	**Iac-Ist**	**Ipv**	**Pac**	**Uac**	**Upv-Ist**	**Upv-Soll**
hh: mm	Hz	mA	mA	W	V	V	V
5:00	0	0	18	0	0	194	660
6:00	49.996	274.719	337.222	62.207	27.761	245.244	245.319
7:00	49.978	556.639	563.123	125.705	226.484	253.738	254.025
8:00	49.997	1151.211	1079.211	260.325	226.397	260.472	260.894
9:00	50.017	2308.934	2347.033	521.566	226.044	236.762	237.066
10:00	49.998	4009.164	3846.869	912.902	227.766	252.623	252.934
11:00	49.998	5752.862	5738.041	1321.78	229.814	247.821	247.959
12:00	49.987	6351.541	6398.967	1456.465	229.307	245.77	236.992
13:00	49.983	4313.114	4186.61	982.195	227.642	250.317	250.593
14:00	50.017	4998.5	4864.984	1154.315	230.715	253.073	249.419
15:00	49.991	3590.138	3455.707	829.862	230.898	255.634	254.715
16:00	49.989	1896.523	1865.548	435.677	229.881	249.605	249.855
17:00	49.98	4294.967	4179.691	991.78	230.903	252.862	253.187
18:00	49.99	817.142	835.858	187.208	229.46	247.15	247.25
19:00	49.953	18.742	43.691	4.216	227.708	246.371	595.175
20:00	0	0	0	0	0	0	0

In this way, the NDZ of the passive over/under voltage method is to be reduced to zero and provides a safe protection without undermining the output power quality. The algorithm proposed for solving the problem of passive over/under voltage methods is presented in Fig. 3.

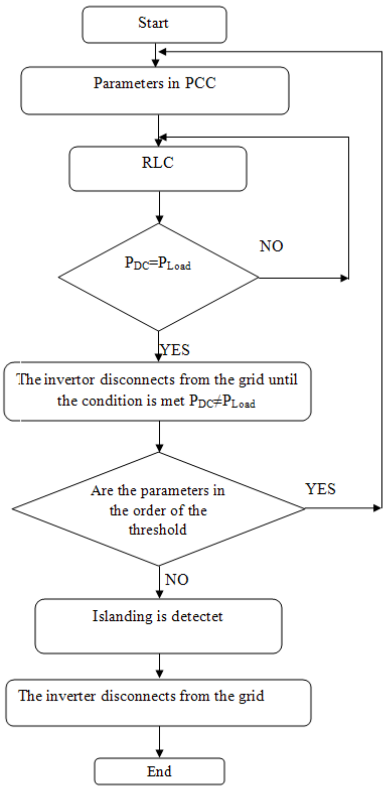

Fig. 3. The proposed algorithm for solving the worst case detection problem

To justify the operation of such algorithm, we also implemented simulations using Matlab Simulink software. The simulations carried out are part of the passive methods of protection from the creation of isolation circumstances, and such topologies include The topology of automatic power management and Topology of over/under stress protection. It is worth noting that the simulations of the automatic power management method typically belong to the workflow in the proposed algorithm for solving the problem of passive methods.

Figure 4 shows the topology for detection under/over voltage and under/over frequency with inverter shutdown. The voltage at PCC can only change when the grid is disconnected and DC power and power load are not the same. If the load power is smaller than the voltage at PCC increases and if the load power is higher than the voltage at PCC decreases. Voltage difference depends on the difference between these powers.

The simulation procedure is: The maximum inverter power is 3.9kW, is the same as the maximum power of the PV system within FECE. In the period of 0.15s till 0.25s, the local charge is doubled, so up to 6.4 kW. Under normal conditions, the power of the local load lies in 3.2kW.

- If the load power P_{ng} rises above 3.9kW, the inverter automatically switches off, while the electrical utility grid switches on.
- If the load power P_{ng}lies between 0.7P_{inv} (70%) and P_{inv} (100%), or 2.73kW to 3.9kW, then disconnects the electrical utility grid and local loads are supplied only by the PV inverter.
- If the load power P_{ng}falls below 70% of the maximum inverter power (i.e. below 2.73kW), In this case, both are connected, the PV inverter and the electrical utility grid, so that over-output of the inverter is transferred to the electrical grid. Simulation is performed for the range 0.0s to 0.3s.

For a better understanding of the application of the method in question we can compare two parameters:
• Maximum Inverter Power P_{inv}, and
• Local power load P_{ng}

When the condition is met:
P_{ng}> P_{inv}, the electrical grid is connected, while the PV inverter is disconnected.
When the condition is met:
70%P_{inv}< P_{ng}< P_{inv}, the electrical grid is disconnected, while the PV inverter is connected.
Ultimately when the condition is met: P_{ng} < 70%P_{inv}, the electrical grid and Pv inverter also connects.

So all this is done for P_{inv} = 3.9kW, and 70%P_{inv} = 2.73kW.

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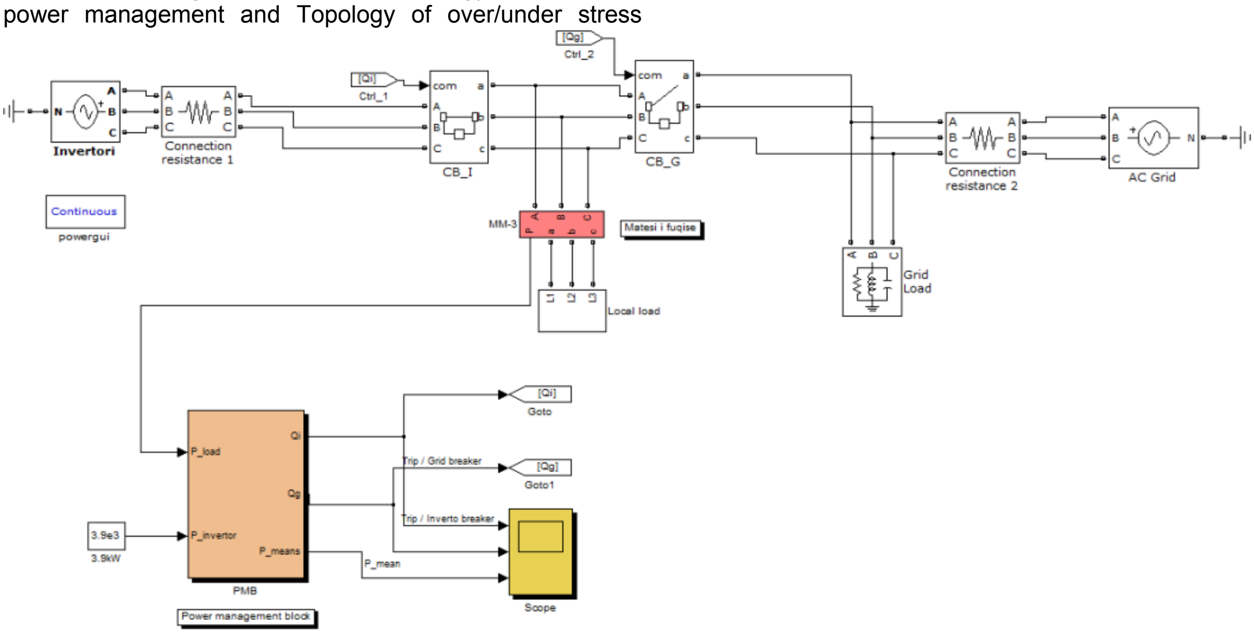

Fig. 4. Topology of the Active Power Utilization Circuit

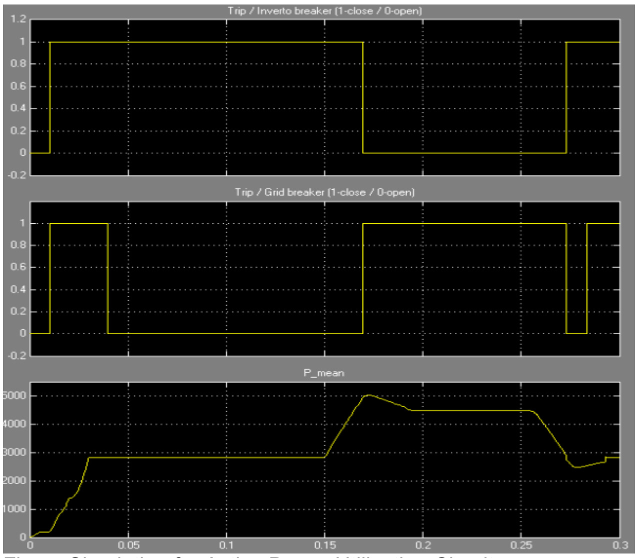

Fig. 5. Simulation for Active Power Utilization Circuit

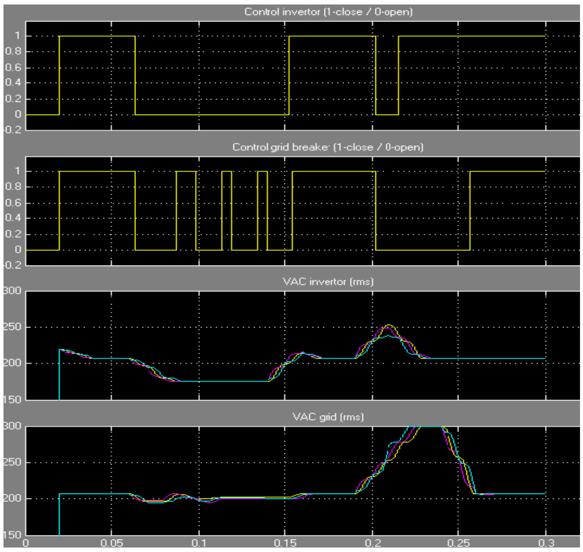

Fig. 7. Simulations for protection over/under voltage topology

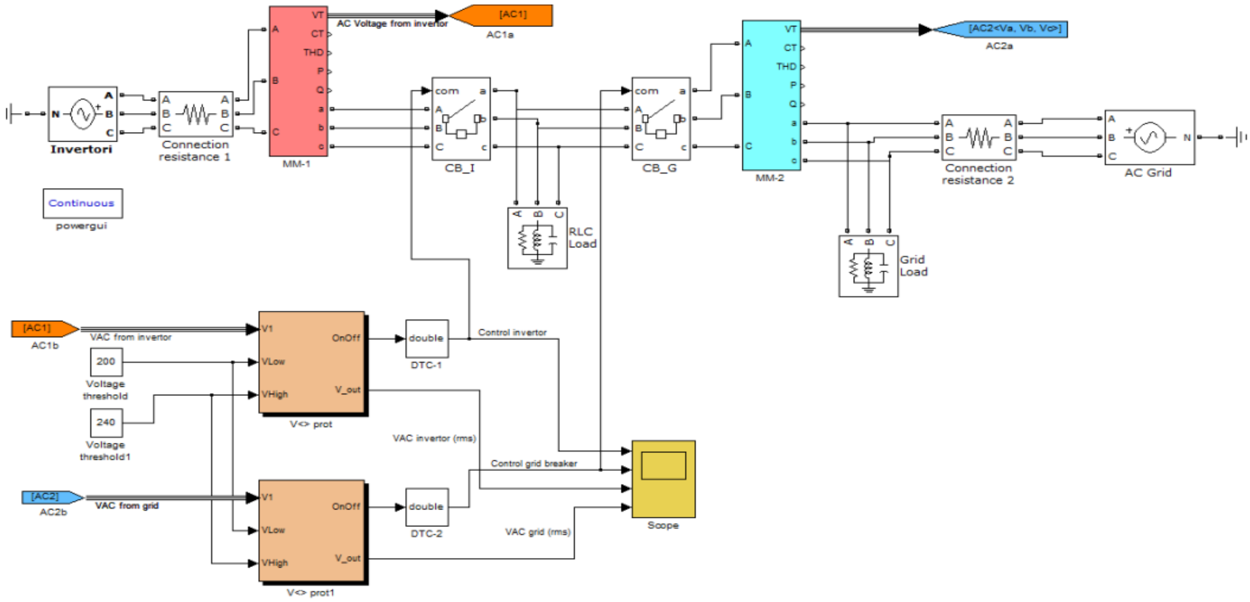

Fig. 6. Model used to simulate the method

In Fig. 5 are presented simulations carried out for the abovementioned conditions of the Active Power Utilization Circuit. The block diagram of the system resulting from the design can be observed in Fig. 6. For the developing of the process of simulations, the software Matlab/Simulink has been used. Simulation is performed for the interval 0.0s till 0.3s.The Under Voltage Protection is set to 200V, and the Over Voltage Protection is set to 240V.

In the first interval, from 0.06s till 0.14s the inverter voltage drops to 80% of the nominal value, and in this case, the inverter disconnects itself until the voltage reached by the predetermined threshold limit values.

In the second period, from 0.19s to 0.24s the network voltage is simulated to rise above 45% of the nominal value, in which case the inverter is disconnected to protect itself from the consequences of the voltage. Namely, when the control system registers an RMS voltage higher or lower than that permitted, it produces the STOP signal. The value of this voltage for the simulation performed is represented in Fig. 7.

Conclusions

Creating of the so-called isolation of generators connected to the network can occur when the service system which consists of generators such is disconnected from the main grid and generators independently continue to energize the remainder under insulation (island). In this paper are analyzed some passive methods for detection of islanding of distributed generators, and especially for applications based on the inverter. Also, seeing that the inverter is the most important components of PV system components are cited on three types of basic inverters considered for use in PV systems. In the analysis it was concluded that the passive methods in general, specifically the methods passive over / under voltage and over / under frequency has many good protecting features in case of submission of islanding, does not require districts additional implementation and does not degrade the quality of output power but has a non-detection zone wide enough. This non-detection area reduces confidence in the use of this method, leaving no room for adequate detection method of isolation of the circumstances of the method in question.

Seeing the need inalienable intervention methods passive protection and distribution system FV network, and considered not suitable and not very safe protection based on more methods, in the last analysis It has been proposed algorithm which eventually solve the problem of the non-detection zone without causing degradation of quality output power. The algorithm is based on an additional relay protection system within which function as switches whenever PV energy produced by the system is equal to the energy that gets loads, staying connected as long as the opposite. This additional relay is not expected to cause any side effects even in PV system or network service or load, but will definitely solve the problem of NDZ, displayed the passive methods.

While the problem of occurrence of the circumstances of isolation when NDZ located in areas shaded, it is found that can be solved using inverter Cell Solar, which eliminates effectively the possibility of submission of NDZ's but in current systems PV it deemed not suitable to be applied.

Finally notice that the algorithm proposed problem of finding methods cited in this paper solved effectively, and, in the future research should be directed at finding a method practical to eliminate conditions of islanding when NDZ located in areas shaded, knowing that our country is characterized by a relief that creates such cases.

This results obtained from monitoring a 3.9 kWp grid-connected photovoltaic system installed on a flat roof of a laboratory building of FECE in Prishtina, Kosovo (Latitude 42.6667°N and longitude 21.1667°E).

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