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Acronyms and Abbreviations

ANN – Artificial Neural Network
DG – Distributed Generation
DSA – Dynamic Security Assessment
FESS – Flywheel Energy Storage System
LC – Load Controller
LV – Low Voltage
MC – Microsource Controller
MG– MicroGrid
MGCC – MicroGrid Central Controller
MS – Microsource
MV – Medium Voltage
PV– Photovoltaic
SOFC – Solid Oxide Fuel Cell
SSMT – Single-Shaft Microturbine
VSI – Voltage Source Inverter
DT – Decision Tree
OP – Operating Point
LS – Learning Set
TS – Testing Set

1. Introduction

The interconnection of small modular generation systems (PV, fuel cells, micro-turbines, small wind generators) and storage devices to Low Voltage (LV) distribution grids will lead to a new energy system paradigm, usually referred as the MicroGrid [1]-[5]. These microsources (MS) are small units of less than 100 kWe, most of them with power electronic interfaces, using either renewable energy sources or fossil fuel in high efficiency local co-generation mode. A MG can be an extremely flexible cell of the electrical power system, being able to be operated interconnected to the main power system or autonomously in case of emergency situations if endowed with proper control and management systems [1]-[5].

A typical MG architecture is presented in Fig. 1. The MG operation philosophy is based on an hierarchical type control approach headed by the MicroGrid Central Controller (MGCC) [3]-[4]. A network of controllers with local intelligence (Load Controller (LC) and Microsource Controller (MC)) has to be installed, defining a secondary layer in the hierarchical control structure. In this control hierarchy, the information to be exchanged should be limited to the minimum information necessary to achieve a large effectiveness and autonomy, namely during emergency operation. The results presented in [4] highlight that under abnormal operating conditions only a network of local controllers can deal effectively with the resulting transient phenomena. With an intelligent distributed approach where the local controllers (MC and LC) will act, in a very fast way, as independent agents and making an efficient use of the local resources, it will be possible to maintain system operation in an islanding condition. However, frequency control problems arise during islanding operation due to the slow response of MS to control signals and due the inexistence of rotating masses directly connected to the grid (inertialess system). Sudden islanding of the MG due to faults occurring in the MV network may cause high unbalances between local load and generation which must be compensated by local MS and through a very efficient use of storage devices and load shedding mechanisms [4]. Therefore, the MG

control strategies presented in [4] must be complemented with additional features, in order to guarantee a seamless transition to islanding operation. These features involve an adequate management in a real time environment of three resources: power production, local energy storage and loads (load shedding).

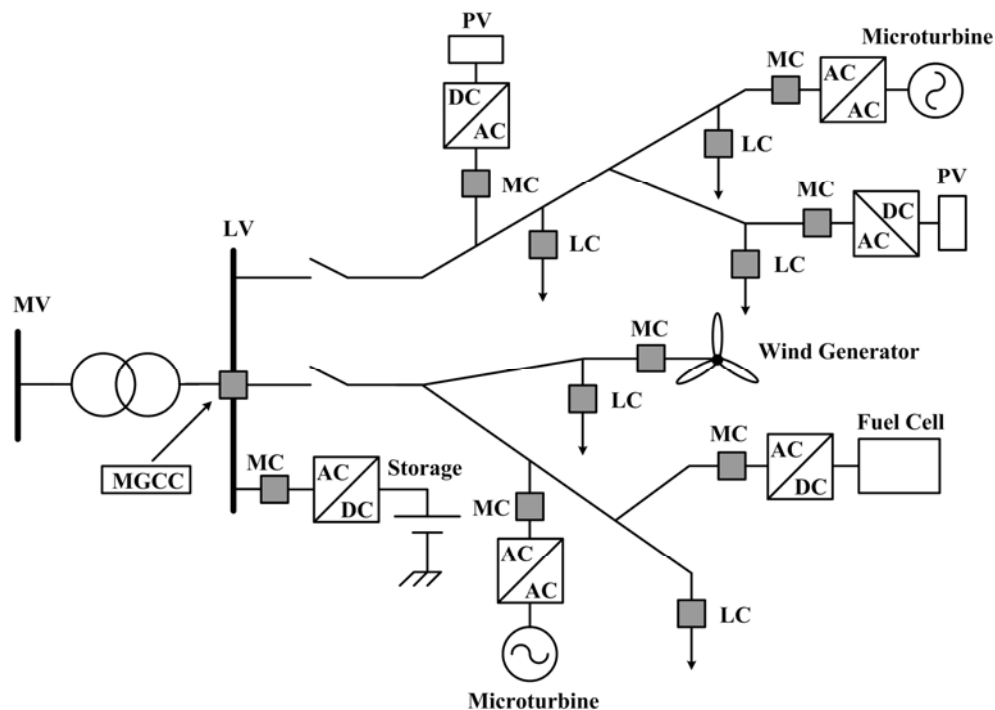


Fig. 1 – MG architecture, comprising MS, loads and control devices

The on-line management of such resources requires knowledge about the MG dynamic behavior for each specific scenario. For each disturbance to be considered, the traditional and most accurate analysis involves the numerical solution of a system of non-linear equations, which is a very demanding and time consuming computational task and it is not suitable for on-line purposes. Therefore, artificial intelligence based tools, such as Artificial Neural Networks (ANN), are alternative approaches since they provide effective means of extracting high level knowledge from large data sets in order to help on-line system management regarding these dynamic issues. The referred data sets should contain detailed information about MG dynamic behavior. This information

should be generated off-line by making use of appropriated simulation platforms, which were previously developed within the MICROGRIDS project [4]. Moreover, ANN have fast time responses which are adequate for real time response and provide an analytical tool to compute derivatives of a security parameter relatively to the control variables in order to compute the preventive control actions [6], [8].

The scenario previously described resembles the application of Artificial Intelligence techniques to Dynamic Security Assessment (DSA) in conventional power systems, which has been widely developed in the last years. As illustrative examples, in [6]-[8] are presented successful cases of ANN and decision trees application in the field of DSA in conventional power systems with high levels of renewable power penetration. For each operating scenario a fast dynamic security evaluation is performed and if insecurity is detected new alternative stable points are suggested. This approach leads to higher penetration of renewable and contributes to assure a secure operation of isolated power systems.

Following the application of DSA techniques to conventional power systems, an approach was developed in order to efficiently management storage devices, power production and load shedding during MG islanding operation aiming to assist the MGCC on the fast and reliable identification of MG insecure operating conditions and on the definition of corrective measures in order to guarantee system survival. MG communication infrastructure and the hierarchical control system shown in Fig. 1 are of paramount importance for the effective application of such a procedure. The MG management and control system will be responsible for taking system measurements to perform security analysis and communicate the remedial measures to MG local controllers.

The main goal of this analysis is to evaluate and, if possible, to predict the preservation of a safe operating mode following MG islanding (seamless transaction) based on a determined set of conditions of the various microsources and loads in the LV network (different operating scenarios). This analysis will hopefully provide (in an operational time basis) valuable information about the

robustness of the microgrid, allowing the MGCC to define a more robust operation strategy in order to guarantee that, under a determined set of conditions, moving from interconnected operation mode to islanding operation mode can be done safely. By performing DSA in a MG, it is possible to increase customer benefits arising from such an ambitious exploitation of DG integration in LV distribution networks.

2. Energy Balancing in the MicroGrid

A system with clusters of MS designed to operate in an island mode requires some form of storage to ensure initial energy balance during transients [1-5]. The necessary storage can come in several forms: batteries or supercapacitors on the DC bus for each MS or by a direct connection of storage devices to the AC system (e.g. flywheels). Storage devices management is of great importance for successful MG operation in islanded mode, with the load shedding procedure assuming also very high importance to avoid fast and long frequency deviations [4].

Flywheel Energy Storage Systems (FESS) are becoming competitive with chemical batteries, mainly for short term power storage with frequent charge/discharge cycles. They can be used to supply highly efficient and reliable electric power for seconds or minutes at a time [9]. FESS is able to provide very high power, which is only limited by the rating of the generator and power electronics. The response time is limited to a few milliseconds and the number of charge and discharge cycles is constrained only by the efficiency of the electric and power electronic system cooling [10]. FESS applications in MG are very promising since flywheel offer the advantage of a longer lifetime, high efficiency and greater depth of discharge than batteries [9]-[11]. Furthermore, and in contrast to what happens in chemical batteries, state of charge determination in FESS is very easy, since it depends only on its speed of rotation.

A critical security trait for MG operation is to ensure they can run into islanding operation following an unexpected event without collapse due to insufficient

energy storage. When the MG is interconnected with the upstream MV network all the transients are taken by the main power system. Depending on the MG operating conditions, such as local load, local generation profile and MS availability for active power/frequency regulation, high amounts of energy may be required to be injected in the MG in the first moments subsequent to islanding. Due to the slow response of controllable MS to control signals, the most significant part of this energy must be provided by FESS, which has a finite storage capacity. This problem is related to frequency stability, since it depends on the MG ability to restore balance between load and generation during islanded conditions and with the minimum loss of load.

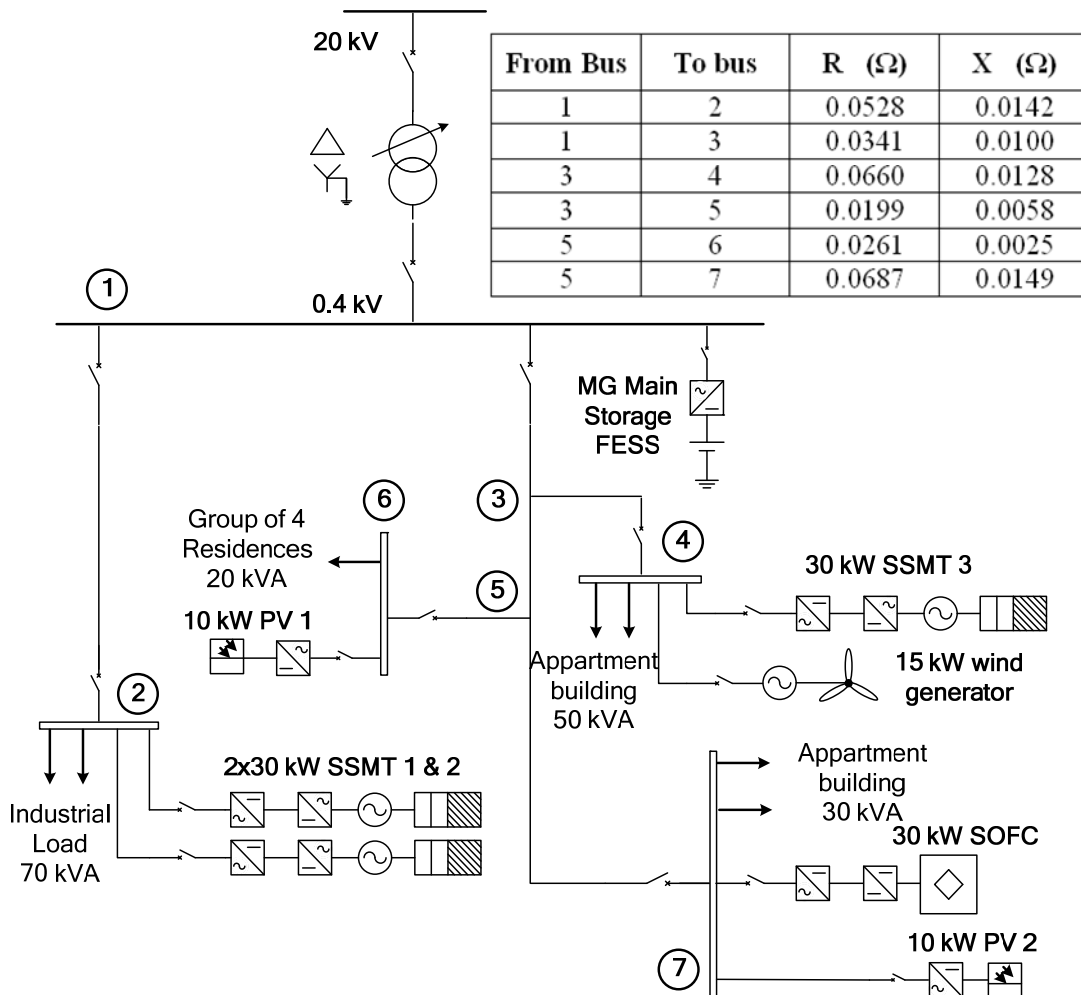


Fig. 2 – MG test system

In order to illustrate the referred issues, a simple example is presented next. The single line diagram of the LV test system used in this research is shown in Fig. 2. This LV test system comprises an industrial load, a LV distribution feeder serving a residential area, several MS connected to the grid and a FESS to allow MG running into islanding operation. The values of the loads shown in Fig. 2 corresponded to simultaneous load values for this LV grid.

Table 1 – Scenarios characterization

	Case		
	1	2	3
SSMT 1 + SSMT 2 Active Power (kW)	6,5	41,1	24,4
SSMT 3 Active Power (kW)	4,7	13,4	24,3
SOFC Active Power (kW)	14,9	29,9	29,5
PV1 + PV2 Active Power (kW)	4,8	16,2	2,5
Wind Generator Active Power (kW)	6,31	13,9	3,7
Power Imported from the MV Network (kW)	55,7	-28,1	65,5

Fig. 3 illustrates typical MG dynamic behaviour and the energy required to be injected by the FESS during and subsequent to system islanding in several operating conditions, which are characterized in Table 1: in cases 1 and 3, the MG is importing power from the MV network and the FESS must inject energy after MG islanding; in case 2, the MG is injecting power into the MV network and therefore the FESS must absorb the energy surplus after MG islanding. In case 3 it is also possible to observe that the MG does not have enough generation capabilities for load/frequency regulation. In this case, MG frequency is not restored to the nominal value and the FESS will kept injecting energy, which is not an admissible situation due to its limited storage capacity.

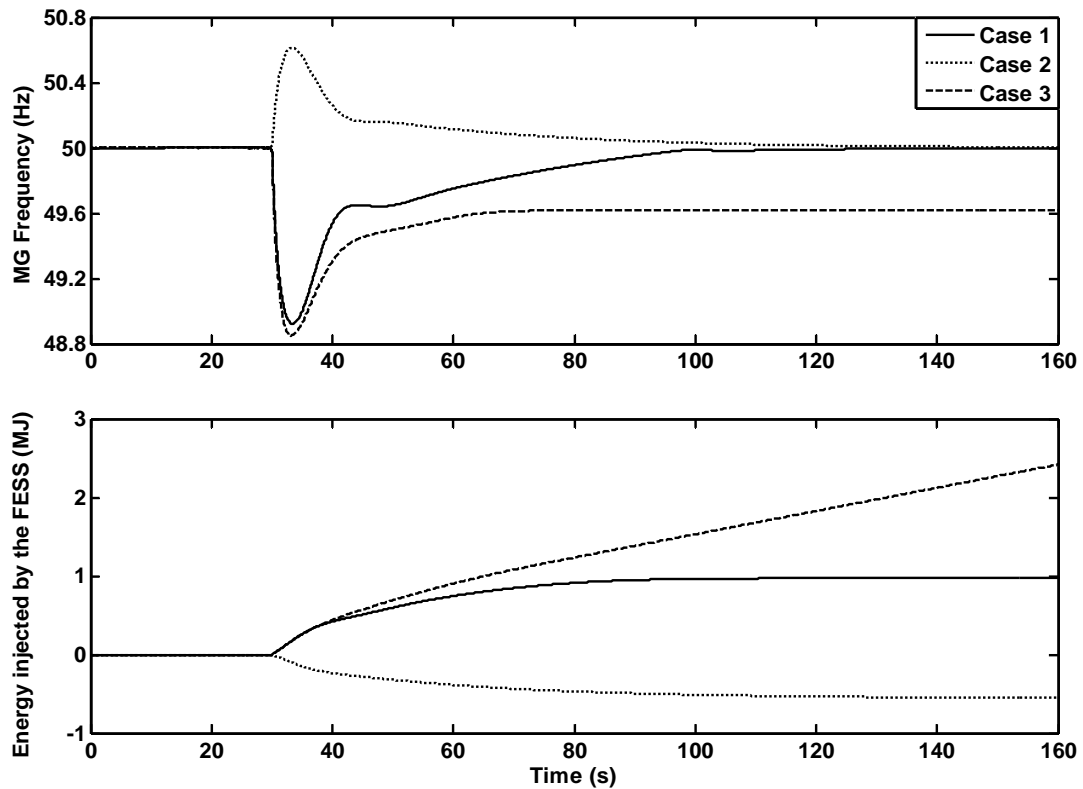


Fig. 3 – Frequency and energy injected by FESS for several operating conditions during and subsequent to MG islanding

3. MicroGrids Security Assessment

The application of ANN to perform DSA involves four major steps:

- Identification of the security problem
- Data set generation
- Security structure design
- Definition of preventive control actions

All these steps are to be performed off-line. The final product of the procedure – the security structures – are to be used in an on-line environment as a software module of the MGCC or to obtain physical interpretation of the system behaviour.

The identification of the MG dynamic security problem involves a procedure of understanding its dynamic behaviour, namely the identification of potential situations for which the system may lose stability. This step relies on time domain dynamic simulation of fully defined system models. Thus the simulation platform and the control strategies presented in [4] were used to generate the required data set. The simulation platform includes dynamic models for several types of MS (SOFC, SSMT, micro-wind generators and PV) and the correspondent power electronic interfaces, as well as the network control functions. The general MG control strategy assumed in this report is based on the Single Master Operation principle described in [4]. Thus, the MG includes a storage device, which is responsible for balancing load and generation during MG islanding operation. The other controllable MS such as fuel cells and microturbines respond to the load-frequency control system according to the strategy presented in [4].

The data set generation procedure consists of a data set of samples that reflects the dependency of the system behaviour (i.e., the security index) with variations in its operating conditions. Each data set operation point can be characterized by a large number of system variables. However, ANN inputs should be selected taking into account that they are able to conveniently characterize system behaviour and are small enough to avoid a large number of ANN parameters. The ANN inputs should also contain a set of monitorable and controllable variables in order to exercise preventive control actions upon the system if insecure operation conditions are detected [6]. Furthermore, these variables should be directly obtained from the MGCC data base, which periodically receives information about MG operating conditions. Most of these variables are related to MS power production levels and to MG load.

3.1 Identification of the MicroGrid Security Problem

In conventional power systems, particularly in the isolated ones, the critical issue for assessing dynamic system security is the frequency deviation or the rate of change of the frequency following some pre-identified disturbances, which may

lead to load curtailment or to generation tripping due to the activation of frequency relays [6]-[8]. Therefore, the maximum under-frequency deviation, sometimes combined with the rate of change of the system frequency, is chosen as an index for characterising conventional power system security.

In MG operating under islanded conditions, frequency stability problems are related to unbalances between local load and generation. The MG primary frequency regulation method is based on a droop control strategy used in VSI coupled to storage devices (FESS). The droop characteristics can be written as follows [4], [12]-[13]:

$$\begin{aligned} \omega &= \omega_0 - k_P \times P \\ V &= V_0 - k_Q \times Q, \end{aligned} \tag{1}$$

where P and Q are the VSI active and reactive power outputs, k_P and k_Q are the droop slopes (positive quantities) and ω_0 and V_0 are the idle values of the angular frequency and voltage (values of the inverter angular frequency and terminal voltage at no load conditions). If n VSI operates in a standalone AC system, a power variation ΔP in the system is shared among them, such that in steady state the following equations stand:

$$\Delta P = \sum_{i=1}^n \Delta P_i \tag{2}$$

being ΔP_i the power variation in the *i*th VSI. The steady state power variation in each VSI and system frequency can be computed using the following matrix equation:

$$\begin{bmatrix} 1 & k_{P1} & 0 & 0 & \cdots & 0 \\ 1 & 0 & k_{P2} & 0 & \cdots & 0 \\ 1 & 0 & 0 & k_{P3} & \cdots & 0 \\ \cdots & \cdots & \cdots & \cdots & \ddots & \vdots \\ 1 & 0 & 0 & 0 & \cdots & k_{Pn} \\ 0 & 1 & 1 & 1 & \cdots & 1 \end{bmatrix} \times \begin{bmatrix} w' \\ \Delta P_1 \\ \Delta P_2 \\ \Delta P_3 \\ \vdots \\ \Delta P_n \end{bmatrix} = \begin{bmatrix} w_{grid} \\ w_{grid} \\ w_{grid} \\ \vdots \\ w_{grid} \\ \Delta P \end{bmatrix} \quad (3)$$

where w' is the post-disturbance MG angular frequency and $w_{grid} = w_{oi} - k_i \times P_i$ is the pre-disturbance MG angular frequency.

Using Eq. 3, it is possible to compute MG frequency deviation following a generation or load variations ΔP during islanding conditions. Eq. 3 shows also that frequency variation in the islanded MG is perfectly controlled by the droop settings and therefore easily predicted. Hence, In contrast to what happens in conventional power systems, frequency deviation is not an important issue to characterize MG security. A critical issue to ensure MG does not collapse due to insufficient energy storage to balance load and generation during islanding conditions is to ensure that FESS do not run out of energy. For this reason, a suitable index to evaluate MG security following each pre-defined disturbance is the energy E required to be injected in the islanded MG (or absorbed from the islanded MG) in order to balance local load and generation, while controllable MS such as microturbines and fuel cells respond to the secondary load-frequency control proposed in [4]. The MG is considered insecure if the energy required to be injected or absorbed by the FESS is out of its physical limits.

3.2 Design of the Security Assessment Tool

The results presented in Fig. 3 do not take into account the limited storage capacity of the FESS. Nevertheless, these results illustrate the need of a fast and efficient toll for an on-line prediction of the energy required to be injected /

absorbed in the MG following system islanding and for determining remedial actions if an insecure state is detected. The main goal is to obtain a relationship between pre-contingency MG parameters, able to predict the energy required to be injected by the FESS, and to determine remedial actions for insecure operating scenarios.

3.2.1 Data Set Generation Procedure

A structured Monte Carlo sampling method [14] was used in order to generate knowledge about MG dynamic behaviour, since it demonstrates to provide a well distributed and highly representative data set throughout the defined operating range, which is of paramount importance for the design of robust security assessment tools. The MG operating conditions that influence its behaviour regarding the proposed security index are identified in Table 2. The credible range and the resolution used for each one of the selected variables are also specified in Table 2. Very simple restrictions were considered in the data set generation procedure, and therefore an almost uniform covering of all the possible MG operating scenarios were considered. One of the restrictions is related to power production in valley hours and peak load hours. If the MG load is below 30%, it was considered that the power production in SOFC and SSMT must be lower than 60% of their nominal capacity. Conversely, if the MG load is higher than 60 %, SOFC and SSMT production should be higher than 20 %. Sampling on the PV production for night hours operation is not performed, since its production is zero.

The Monte Carlo parameters of Table 2 correspond to the MG operating conditions in which the sampling method is applied. The definition of the data set resolution was performed by defining the resolution of each Monte Carlo parameter, i. e., the number of intervals of each parameter operating range. By defining the resolution of each of these parameters, the data set operating range (a 6-dimension hyperspace) is divided into hypercells. The data set generation procedure consists on the random sample over the Monte Carlo Parameters of

Table 2, according to the pre-defined operating range and resolution. It is a set by step procedure in which for each hypercell, a pre-defined number of values of the 6-dimension hyperspace are sampled using an uniform distribution for each variable [14].

In order to include some representative knowledge in the data set about MS unavailability due to maintenance or other unplanned reasons, the following procedure was used. The unavailability of controllable MS (SSMT and SOFC) was considered by applying the previously sampling procedure for the data set generation in the following scenarios: unavailability of one SSMT in MG bus number 2, unavailability of SSMT 3 and the unavailability of the SOFC. The unavailability of renewable energy sources is implicitly considered by using the operating range assigned to them, as in Table 2. The simultaneous unavailability of more than one controllable MS was not considered, since it would lead to a MG operating scenario with reduced secondary load-frequency regulation capabilities. In this case, it is assumed that MG islanding is not successful following a disturbance occurring in the MV network. However, the simultaneous unavailability of a single controllable MS and a renewable energy source (PV or micro-wind generator) is possible due to the operating range assumed for the last ones.

Table 2 – Monte Carlo Parameters

Monte Carlo Parameter	Range (p.u.)	Resolution
SSMT 1 + SSMT 2 Active Power	[0.1; 1]	5
SSMT 3 Active Power	[0.1; 1]	5
SOFC Active Power	[0.3; 1]	5
PV1 + PV2 Active Power	[0; 1]	3
Wind Generator Active Power	[0; 1]	3
MicroGrid Agregated (Total) Load	[0.2 1]	5

3.2.2 Artificial Neural Network Design

The use of ANN is intended for an on-line and accurate evaluation of system security relatively to the pre-defined disturbance and intended for extracting high level knowledge from the generated data set.

Each point of the generated data set is characterized by a set of system measurements (physical MG parameters), which will be exploited in order to identify those who have enough discriminating abilities to be used as the inputs of the ANN. In this case, the following set of system parameters is used:

Active power generated by each MS (P_i)

MG total active power (L)

Reserve margin in controllable MS such as SSMT and SOFC ($R_i = P_i^{nom} - P_i$, where P_i^{nom} is the nominal power of each controllable MS).

The variables selected as inputs for the ANN are easily obtained from the MGCC data base, which is periodically updated with data provided by MG local controllers (LC and MC) by using the communication infrastructure. These sets of variables implicitly contain the information required to derive the MG dynamic behaviour characterized by the proposed security index. Thus, the output of the ANN will be the energy E injected / absorbed by the FESS during a time interval of two minutes subsequent to MG islanding. This time interval was chosen taking into account the large number of dynamic simulations performed in order to build the data set and because such time is the one required to obtain a stabilized response of the controllable MS, as it can be observed in Fig. 3.

3.2.3 Derivation of the Preventive Control Strategy

If an unstable MG operating condition is detected, remedial actions must be derived in order to ensure that the MG securely moves to islanding operation in the event of a disturbance in the MV network. As the ANN emulates the behaviour of the energy injected / absorbed by the FESS, the remedial actions can be determined by finding the values of the control variables that satisfy the following constraints for each insecure scenario:

$$\begin{aligned} E &< E_{\max} \\ \text{or} \\ E &> E_{\min} \end{aligned} \tag{4}$$

where E_{\max} is the maximum amount of energy that can be injected by the FESS and E_{\min} the maximum value of the energy that can be absorbed the FESS.

It will be frequent that MG will not have enough generation capabilities in order to supply the entire load during islanding operation, leading to the adoption of load shedding strategies. Furthermore, adding a security constraint to an economic dispatch problem for the MG will increase the electricity price, and it will not be a very likely situation due to the existence of thermal and electric loads, which should be met during the interconnected mode. In case of system islanding such restriction must be relived in order to achieve load-frequency control capabilities. Therefore, it is suggested that in such a case the preventive control strategy will be a load shedding strategy. Determining the minimum amount of load to be shed L_{shed} in order to satisfy the first condition of Eq. 4 can be easily performed through a gradient technique and by computing the derivative $\partial E / \partial L$, as described in [6], in order to solve the equation $E - E_{\max} = 0$.

In other operating conditions the MG can export power to the MV network, as shown in Fig. 3. In this case, the FESS must be managed in order to be able to absorb the power surplus while controllable MS respond to the control signals to reduce the output power. If the FESS is not able to absorb the energy surplus, a preventive control strategy must also be envisaged. Such a preventive control must include the reduction of the output power of some MS. Controllable MS respond to this situation by reducing its power output according to the MG control strategy proposed in [4]. Nevertheless, according to the models adopted for controllable MS, their response to the control signals has an inherent time constant, being desirable to find alternatives to achieve a faster reduction of the power produced within the islanded MG (reduce renewable generation or connect dump loads). Concerning controllable MS, a possible solution is its disconnection from the grid. However, disconnection of SSMT and SOFC has major implication in MG security, because they have long down time periods after shutdown. Therefore, the preventive strategy in this case includes the reduction of the output power in micro-wind or / and PV generators or the connection of dump loads. Determining the minimum amount of power to be reduced in non controllable generators in order to satisfy the second condition of Eq. 4 can also be performed through a gradient technique and by computing the derivatives $\partial E / \partial P_{PV}$ and $\partial E / \partial P_{Wind}$ where P_{PV} and P_{Wind} are the PV and micro-wind generator output power respectively in order to solve the equation $E - E_{min} = 0$. Determining the amount of dump loads to be connected follows a similar approach to the one described for load shedding.

By exploiting the control capabilities offered by the MG local controllers, it will be possible to derive a strategy based on changes in the active power production in MS and in load curtailment that ensures MG will securely move to islanding operation. The derived security structure will run periodically under the MGCC as a software module. If an insecure scenario is detected, the preventive control strategy is applied in order to determine the corrective actions to be performed in case MG islanding occurs. In conventional power systems, the usual practice is to derive corrective actions to be suggested to system operators or to be

included as security constraints in the unit commitment and in the economic dispatch modules [6]-[8]. In the case of a MG, the corrective actions are to be sent as set points to MG local controllers and are activated only if MG islanding effectively occurs. Detection of MG islanding by local controllers will be performed by measuring system frequency. System frequency is also a parameter that will be estimated by another ANN obtained in a similar way to what is done for dynamic security assessment in conventional power systems. This ANN can be used for a precise tuning of local controllers, namely by defining the frequency at which the local control measures will take place.

4. Results and Discussions

The numerical results obtained for the test system presented in Fig. 2 are described and discussed next. In order to generate the corresponding data set, the procedure described in section VI was used. The generated data set contains 9870 operating points, which were split in a training set and a test set containing respectively 2/3 and 1/3 of the total operating points. The training set is used for training the ANN and the test set for performance evaluation purposes. For the ANN design procedure, the MATLAB Neural Network Toolbox was used. ANN parameters were found through the Levenberg-Marquart back propagation algorithm. In order to obtain the best ANN performance, different ANN topologies (number of layers and number of neurons in each hidden layer) were tested. The inputs for the ANN were described in section VI. When dealing with SSMT1 and SSMT2, they are combined and considered as a single unit connected in bus 2. When considering the unavailability of one of the SSMT connected to bus 2, the corresponding nominal generation capability of the bus is set to the nominal power of one of the SSMT. For the other controllable MS, unavailability is considered by setting $P_i = R_i = 0$. Regarding the single line diagram shown in Fig. 2, SSMT 1 and 2 are operated continuously in parallel; therefore, its output power is combined in a single variable corresponding to the total power injected

in the bus number 2. Due to the small geographical span of the MG, it was also assumed that the radiance can be assumed to be equal for both PV 1 and PV 2 and therefore total PV production is combined in a single variable by adding the power production each PV generator.

The results presented next refer to the ANN with the best performance. The ANN has 9 inputs, two hidden layers with 18 and 9 neurons respectively and a single output, which is the proposed MG security index. Fig. 4 depicts the linear regression between the predicted and observed values of the energy injected by the FESS for the MG two minutes after islanding. The obtained performance in terms of the Mean Absolute Error (MAE) and Root Mean Square Error (RMSE) is:

$$MAE : 4.690 \times 10^{-3} MJ$$

$$RMSE : 6.964 \times 10^{-3} MJ$$

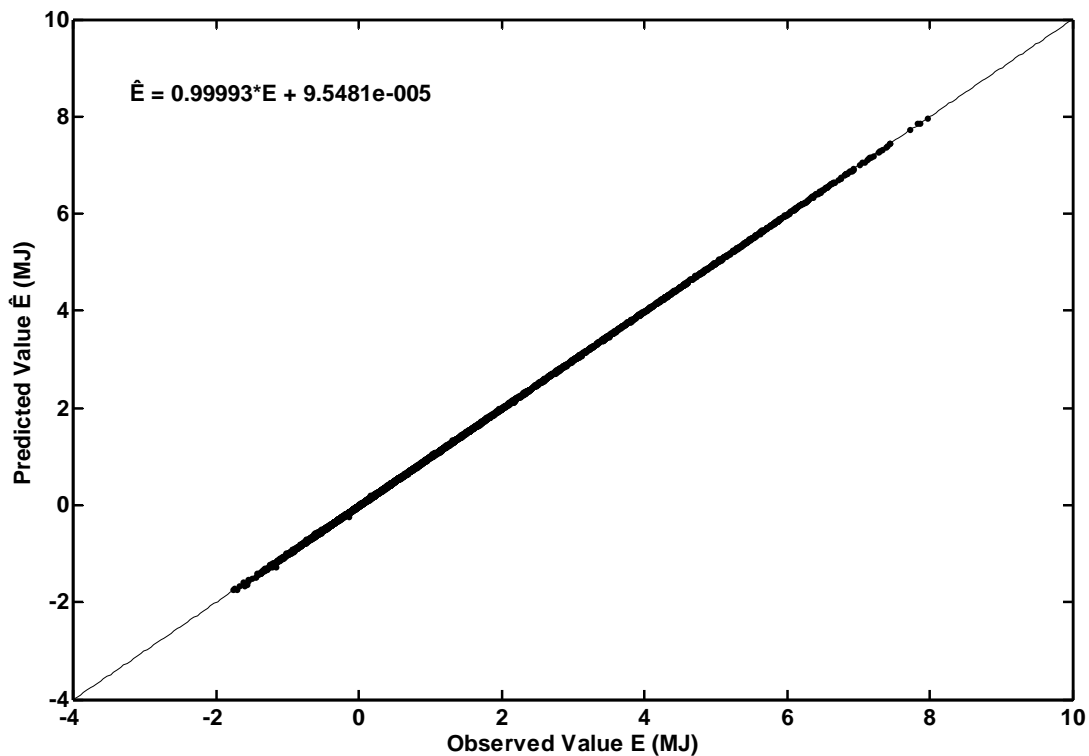


Fig. 4 – Observed and predicted values and the linear regression model results

Despite the simple structure adopted for the ANN to represent MG dynamic behaviour, the performance parameters demonstrate the quality of such a tool for evaluating the dynamic security of a MG.

In order to decide if the MG is operating in a secure or insecure scenario, it is necessary to define the value of the energy that is available to be injected into the islanded system by the FESS. By defining the security condition as $E < 0.8$ MJ, one can use the ANN-based tool in order to calculate the amount of load to be shed for an operating scenario identified as an insecure one by applying the proposed preventive control strategy. For illustration purposes, the procedure is described graphically next. The curves shown in Fig. 5 correspond to three different operating conditions, which are described in Table 3. For these scenarios, all the operating conditions are maintained constant and the MG load is changed in order to plot the graphs. The interception of the horizontal line (corresponding to the energy level of 0.8 MJ) with the energy function of each scenario defines the maximum value the MG load should be in order to not exceed the pre-defined amount of energy that can be injected into the MG during two minutes after islanding. The difference between the actual MG load and the load calculated as stated before corresponds to the amount of load to be disconnected in the moments subsequent to MG islanding (Table 3).

Table 3 – Load Shedding in insecure scenarios

	Case		
	1	2	3
SSMT 1 + SSMT 2 Active Power (kW)	25,49	12,27	26,06
SSMT 3 Active Power (kW)	9,99	7,54	-----
SOFC Active Power (kW)	10,96	13,79	13,93
PV1 + PV2 Active Power (kW)	1,50	6,96	13,53
Wind Generator Active Power (kW)	15,02	-----	11,38
MicroGrid Total Load (kW)	138,81	107,58	122,47
Energy Injected by the FESS (MJ)	1,62	1,27	1,59
Load Curtailment (kW)	28,21	21,14	19,57

The approach developed in this research regards the definition of strategies to assure MG survival at least in a short time interval after an unplanned islanding. However it may happen that the total controllable MS generation capacity is not enough to supply the entire MG load, as can be observed in case 3 (with the unavailability of SSMT3, the controllable generation capability is only in the amount of 90 kW). In this case, even shedding the total amount of load determined by the preventive control strategy, the MG load is still higher than the MG capacity provided by controllable MS. In this case there is a problem related with the provision of reserve during islanding operation, which is not considered in this report. Provision of reserve in islanded MG will also make use of load curtailment mechanisms. In such cases, an additional amount of loads must be shed and can be roughly determined by considering a certain percentage of the total controllable MS capacity as a reserve margin. Disconnection additional loads until this reserve margin is satisfied can be used for this purpose.

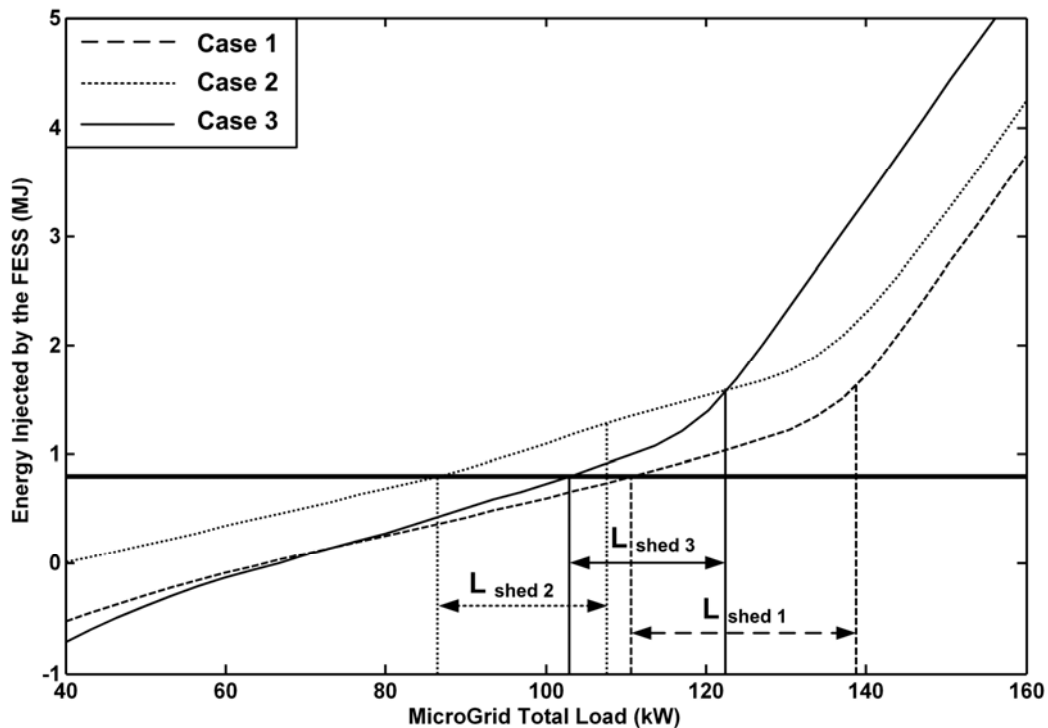


Fig. 5 – Determination of the amount of load to be shed

As an illustrative example, the next figures show the dynamic behaviour of the MG in Case 1 and 3 (scenario characterization in Table 3), before and after the application of the load shedding strategy. The results demonstrate the effectiveness of the load shedding strategy in order to limit the energy injected by the FESS.

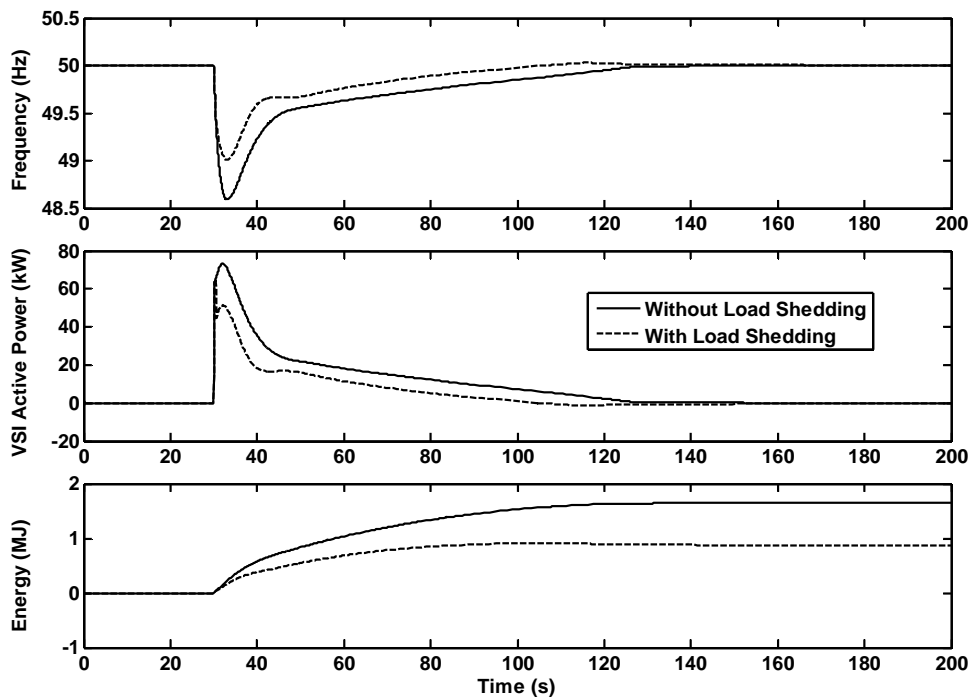


Fig. 6– MicroGrid dynamic behaviour in Case 1

Regarding the scenarios where the MG exports power to the MV network, it was considered that the capacity of the FESS to absorb the energy surplus is 0.8 MJ. In this case, the system is secure if $E > -0.8$ MJ. The results of the application of the refereed strategy to several cases are shown in Table 4. It was found that there are several solutions that lead to a secure operating scenario being the major issue the determination of the total amount of renewable power that must be reduced in the islanded MG. These results suggest the possibility of combining the PV and Wind generators production in a single variable. Therefore, after calculating the total amount of renewable power to be reduced,

the effective power reduction in each generator could be calculated proportionally to the actual power production. However, other rules can be adopted.

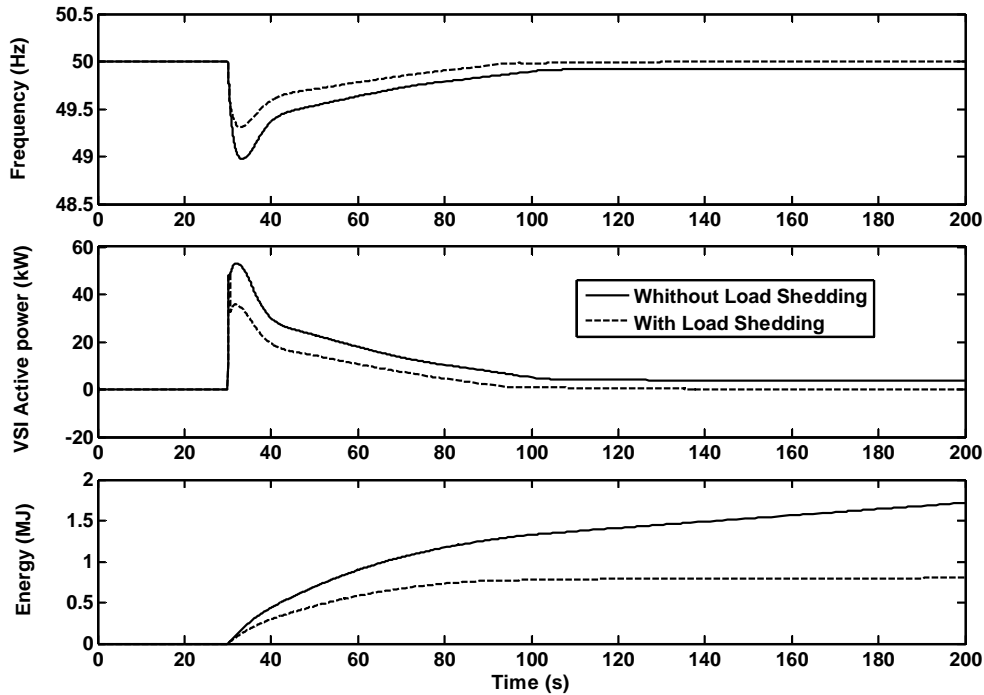


Fig. 7– MicroGrid dynamic behaviour in Case 3

Table 4 – Reduction of Power Production After Islanding in Insecure Scenarios

Energy injected by the FESS (MJ)	-1,07	-1,14	-0,77
Renweable Power Reduction (kW)	11,41	13,44	5,21

If an insecure state is detected, the preventive control strategy determines the amount of load to be disconnected and defines the suitable load shedding set points for each LC. It can also send instructions to the PV and micro-wind

generators MC in order to reduce the output power or even command the connection of dump loads. Each LC or MC will be sensitive to the frequency deviation in order to detect MG islanding and to activate the pre-defined action assigned to them. Therefore, the definition of the frequency level at which the corrective action should take place must also be communicated to local controllers as a set point. An ANN can also be used to forecast the MG frequency deviation as a function of the operating conditions, similarly to the process used to predict the security index. An ANN using the same inputs used for the prediction of the security index and containing two hidden layers with 12 and 6 hidden neurons is able to emulate MG frequency deviation. It presents the following performance indexes:

$$MAE : 0.0031 \text{ Hz}$$

$$RMSE : 0.0039 \text{ Hz}$$

The use of the droops to estimate the frequency deviation introduces considerable errors due to the initial response of controllable MS and to the time constant associated to the VSI. Predicting MG frequency deviation using an ANN tool has a better performance. Combining the information provided by the ANN used to predict the MG security index with the ANN used for the prediction of MG frequency deviation, it is then possible to tune accurately MG local controllers.

5. Decision Trees for DSA and Load Shedding of the MG

Decision Trees (DTs) can be applied on DSA and preventive control of MG. With the DT method, chain rule paths, which lead to secure or insecure operating states of the MG are created. The derived rules of the DT can be used both for DSA and for preventive control of the MG. The method has been applied for DSA and Load Shedding scheme of a conventional power system as described in [15].

5.1 MG Test System

The MG illustrated in Fig. 2 is used for the application of the DTs method for DSA and preventive control of the MG.

5.2 Data Set Generation

The DT method is based on previous knowledge regarding the dynamic behavior of the MG, obtained from a large number of off-line dynamic simulations. The knowledge is organized in a data set comprising a large number of Operating Points (OPs), covering the behavior of the MG in the examined operating region. Each operating point is characterized by a vector of pre-disturbance steady-state variables, called attributes. The data set is split into a Learning Set (LS), used to derive security evaluation structures, and a Test Set (TS) used for testing the developed structures.

A Monte Carlo sampling method was used in order to generate a representative data set, as described in section 3.2.1. The physical limits of the FESS injected energy E_{max} and E_{min} are considered here as additional Monte Carlo parameters; E_{max} is assumed to be a random variable uniformly distributed in $[0, 2,5]$ MJ, while the maximum absorbed energy is $2,5\text{MJ} - E_{max}$.

For each OP the islanding of the MG is simulated using the Matlab/Simulink platform and the frequency as well as the energy required to be injected or absorbed by the FESS within 2 minutes after the islanding is recorded. An OP is considered secure if the following constraints are satisfied

$$E_{min} < E < E_{max} \quad \text{AND} \quad \text{frequency} \in [49,51]\text{Hz} \quad (5)$$

Selected attributes should be monitorable and controllable variables in order to apply preventive control actions under insecure operation. As the suggested preventive control action is load shedding (section 3.2.3), only load-related attributes are utilized. Each OP comprises 44 Attributes as described in Table 5

Table 5 Attributes Used

Attribute description	Attribute Code
P_{load}	A1
$P_{load}-P_{MG}$	A2
$P_{load}-(P_{sofc}+P_{ssmt})$	A3
$P_{load}-(P_{PV}+P_{wind})$	A4
E_{min}/P_{load}	A5
$E_{min}/(P_{load}-P_{MG})$	A6
$E_{min}/(P_{load}-(P_{sofc}+P_{ssmt}))$	A7
$E_{min}/(P_{load}-(P_{PV}+P_{wind}))$	A8
E_{max}/P_{load}	A9
$E_{max}/(P_{load}-P_{MG})$	A10
$E_{max}/(P_{load}-(P_{sofc}+P_{ssmt}))$	A11
$E_{max}/(P_{load}-(P_{PV}+P_{wind}))$	A12
R_{total}/P_{load}	A13
$R_{total}/(P_{load}-P_{MG})$	A14
$R_{total}/(P_{load}-(P_{sofc}+P_{ssmt}))$	A15
$R_{total}/(P_{load}-(P_{PV}+P_{wind}))$	A16
R_{ssmt}/P_{load}	A17
$R_{ssmt}/(P_{load}-P_{MG})$	A18
$R_{ssmt}/(P_{load}-(P_{sofc}+P_{ssmt}))$	A19
$R_{ssmt}/(P_{load}-(P_{PV}+P_{wind}))$	A20
R_{sofc}/P_{load}	A21
$R_{sofc}/(P_{load}-P_{MG})$	A22
$R_{sofc}/(P_{load}-(P_{sofc}+P_{ssmt}))$	A23
$R_{sofc}/(P_{load}-(P_{PV}+P_{wind}))$	A24
P_{MG}/P_{load}	A25
$P_{MG}/(P_{load}-P_{MG})$	A26
$P_{MG}/(P_{load}-(P_{sofc}+P_{ssmt}))$	A27
$P_{MG}/(P_{load}-(P_{PV}+P_{wind}))$	A28
P_{ssmt}/P_{load}	A29
$P_{ssmt}/(P_{load}-P_{MG})$	A30
$P_{ssmt}/(P_{load}-(P_{sofc}+P_{ssmt}))$	A31
$P_{ssmt}/(P_{load}-(P_{PV}+P_{wind}))$	A32
P_{sofc}/P_{load}	A33
$P_{sofc}/(P_{load}-P_{MG})$	A34
$P_{sofc}/(P_{load}-(P_{sofc}+P_{ssmt}))$	A35
$P_{sofc}/(P_{load}-(P_{PV}+P_{wind}))$	A36
$(P_{sofc}+P_{ssmt})/P_{load}$	A37
$(P_{sofc}+P_{ssmt})/(P_{load}-P_{MG})$	A38
$(P_{sofc}+P_{ssmt})/(P_{load}-(P_{sofc}+P_{ssmt}))$	A39
$(P_{sofc}+P_{ssmt})/(P_{load}-(P_{PV}+P_{wind}))$	A40
$(P_{PV}+P_{wind})/P_{load}$	A41

$(P_{PV}+P_{wind})/(P_{load}-P_{MG})$	A42
$(P_{PV}+P_{wind})/(P_{load}-(P_{sofc}+P_{ssmt}))$	A43
$(P_{PV}+P_{wind})/(P_{load}-(P_{PV}+P_{wind}))$	A44

The notation used in Table 5 is described below

- P_{PV} (kW):** Power production in photovoltaic panels
- P_{wind} (kW):** Power production in the small wind generator
- P_{ssmt} (kW):** Power produced in the set formed by the SSMT1, SSMT2 and SSMT3
- P_{sofc} (kW):** Power production in the SOFC
- P_{load} (kW):** Total MG active load
- P_{MG} (kW):** Power produced by the MSs of the MG
- R_{ssmt} (kW):** Reserve Margin in the set formed by the SSMT1 and SSMT2 and SSMT3
- R_{sofc} (kW):** Reserve Margin of the SOFC
- R_{total} (kW):** Total Reserve Margin of the SSMTs and the SOM

The data set comprises 9000 OPs and is split randomly to the Learning Set and the Testing Set (Table 6)

Table 6 Data Set

	Number of OPs	Secure OPs	Insecure OPs
Learning Set	6000	3677	2323
Testing Set	3000	1926	1074

5.3 Decision Tree Construction

Fig. 8 illustrates the Decision Tree for DSA. The nodes of the D.T. have the following scheme: In the upper right side is the number of OPs, which belong to the node. In the upper left side is the label of the node. In the middle is the safety index. Finally in the bottom is the dichotomy test of the node or the characterization of the node as deadend or leaf. In case there is a separation criterion, if it is true the left path is chosen, otherwise the right one.

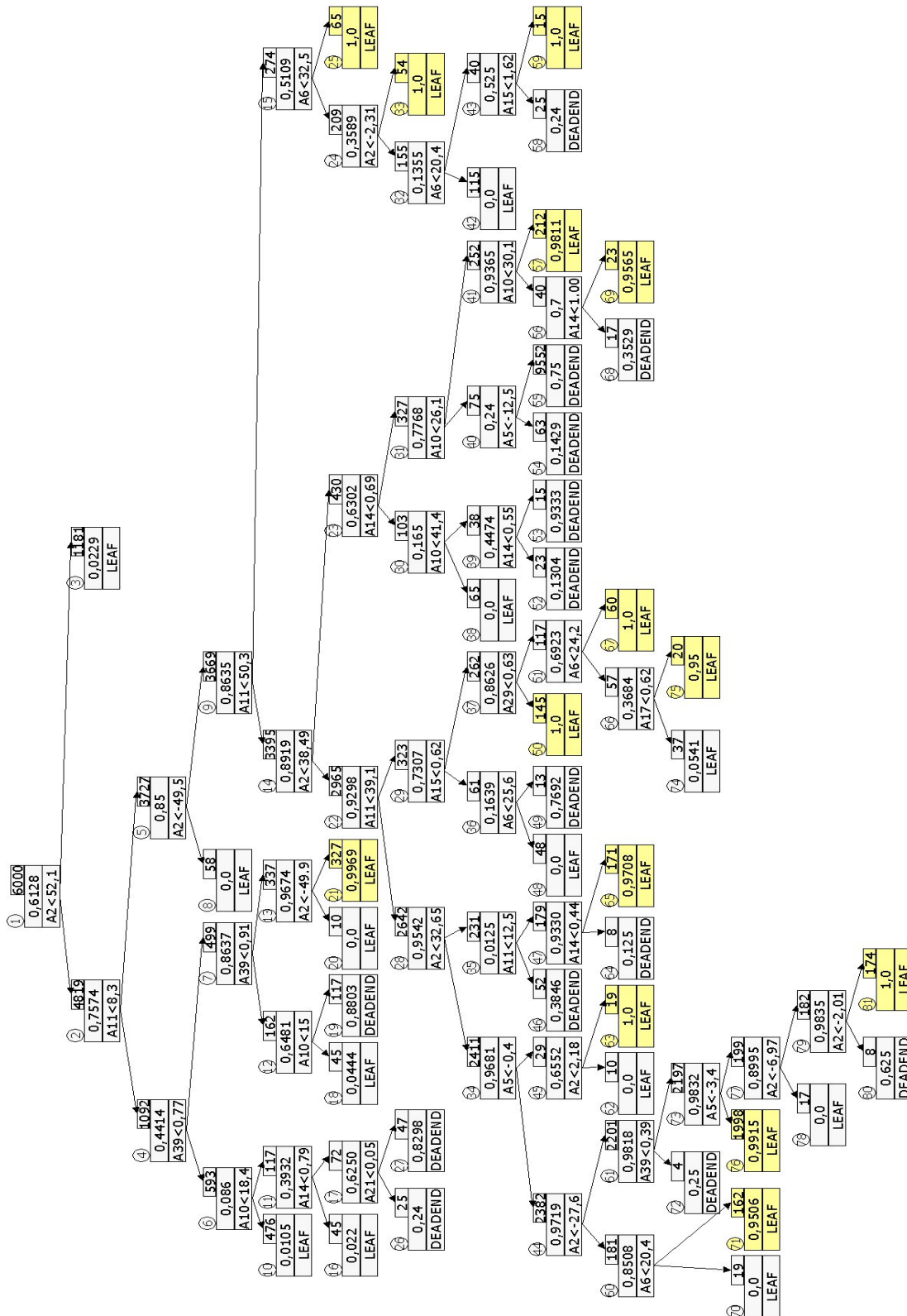


Fig. 8 Decision Tree for DSA and Load Shedding

The rules derived from the DT are applied to the Testing Set, in order to evaluate the performance of the DT to the Dynamic Security Assessment of the system. The results are illustrated on Table 7

Table 7 DT Classification Performance (based on Testing Set)

	Success Rate	Missed Alarms	False Alarms
Learning Set	97.37% (5842/6000)	1,88% (69/3677)	3,83% (89/2323)
Testing Set	95,9% (2877/3000)	3,37% (65/1926)	5,40% (58/1074)

The secure leaves of the DT illustrated in Fig. 8 are 14, (Leaf 21, 25, 33, 50, 57, 59, 63, 65, 67, 69, 71, 75, 76, 81). Each of these leafs corresponds to a constraint set, which is described in Table 8. For the secure transition of the MG to the islanded mode, at least one of these constraint sets must be satisfied. The maximum value of the active load of the MG that satisfies at least one of the constraint sets of Table 8 can be easily found for each operating state by simple calculations and determines the amount of load that needs to be shed, or the dump load that shall be added.

Table 8 Security Constraint Sets extracted by the DT.

Load Zone 1	
CS1 Leaf21	$(A2 > -49,9) \cap (A39 > 0,91) \cap (A39 > 0,77) \cap (A11 < 8,3) \cap (A2 < 52,1)$
CS2 Leaf25	$(A6 > 32,5) \cap (A11 > 50,3) \cap (A2 > -49,5) \cap (A11 > 8,3) \cap (A2 < 52,1)$
CS3 Leaf33	$(A2 > -2,31) \cap (A6 < 32,5) \cap (A11 > 50,3) \cap (A2 > -49,5) \cap (A11 > 8,3) \cap (A2 < 52,1)$
CS4 Leaf50	$(A29 < 0,63) \cap (A15 > 0,62) \cap (A11 > 39,1) \cap (A2 < 38,94) \cap (A11 < 50,3) \cap (A2 > -49,5) \cap (A11 > 8,3) \cap (A2 < 52,1)$
CS5 Leaf57	$(A10 > 30,1) \cap (A10 > 26,1) \cap (A14 > 0,69) \cap (A2 < 38,49) \cap (A11 < 50,3) \cap (A2 > -49,5) \cap (A11 > 8,3) \cap (A2 < 52,1)$
CS6 Leaf59	$(A15 > 1,62) \cap (A6 > 20,4) \cap (A2 < -2,31) \cap (A6 < 32,5) \cap (A11 < 50,3) \cap (A2 > -49,5) \cap (A11 > 8,3) \cap (A2 < 52,1)$
CS7 Leaf63	$(A2 > 2,18) \cap (A5 > -0,4) \cap (A2 < 32,65) \cap (A11 < 39,1) \cap (A2 < 38,49) \cap (A11 < 50,3) \cap (A2 > -49,5) \cap (A11 > 8,3) \cap (A2 < 52,1)$
CS8 Leaf65	$(A14 > 0,44) \cap (A11 > 12,5) \cap (A2 > 32,65) \cap (A11 < 39,1) \cap (A2 < 38,49) \cap (A11 < 50,3) \cap (A2 > -49,5) \cap (A11 > 8,3) \cap (A2 < 52,1)$

CS9 Leaf67	$(A6 > 24,2) \cap (A29 > 0,63) \cap (A15 > 0,62) \cap (A11 > 39,1) (A2 < 38,49) \cap (A11 < 50,3) \cap (A2 > -49,5) \cap (A11 > 8,3) \cap (A2 < 52,1)$
CS10 Leaf69	$(A14 > 1,0) \cap (A10 < 30,1) \cap (A10 > 26,1) \cap (A14 > 0,69) \cap (A2 < 38,49) \cap (A11 < 50,3) \cap (A2 > -49,5) (A11 > 8,3) \cap (A2 < 52,1)$
CS11 Leaf71	$(A26 > 20,4) \cap (A2 < -27,6) \cap (A5 < -0,4) \cap (A2 < 32,65) \cap (A11 < 39,1) \cap (A2 < 38,49) \cap (A11 < 50,3) \cap (A2 > -49,5) (A11 > 8,3) \cap (A2 < 52,1)$
CS12 Leaf75	$(A14 > 0,62) \cap (A6 < 24,2) \cap (A29 > 0,63) \cap (A15 > 0,62) \cap (A11 > 39,1) \cap (A2 < 38,49) \cap (A11 < 50,3) \cap (A2 > -49,5) (A11 > 8,3) \cap (A2 < 52,1)$
CS13 Leaf76	$(A5 < -3,4) \cap (A39 > 0,39) \cap (A2 > -27,6) \cap (A5 < -0,4) \cap (A2 < 32,65) \cap (A11 < 39,1) \cap (A2 < 38,49) \cap (A11 < 50,3) \cap (A2 > -49,5) (A11 > 8,3) \cap (A2 < 52,1)$
CS14 Leaf81	$(A2 > -2,01) \cap (A2 > -6,97) \cap (A5 > -3,4) \cap (A39 > 0,39) \cap (A2 > -27,6) \cap (A5 < -0,4) \cap (A2 < 32,65) \cap (A11 < 39,1) \cap (A2 < 38,49) \cap (A11 < 50,3) \cap (A2 > -49,5) (A11 > 8,3) \cap (A2 < 52,1)$

6. Conclusion

This report describes the application to MicroGrids of the Dynamic Security Assessment concept and the derivation of preventive control measures to allow successful grid islanding. The use of such tools is of paramount importance for the on-line MG operation and management, aiming the seamless transition to islanding operation after the occurrence of contingencies in the main power system. From results obtained in a LV test MicroGrid it is possible to conclude that the derived approach provided encouraging results. In fact, reduced test errors demonstrate the quality and the feasibility of the proposed security assessment too when dealing with this problem. This approach allows coping with a wide range of operating scenarios.

The tool used to predict the energy injected by the FESS following MG islanding can be further exploited in an optimization process in order to define the sizing of MG storage devices, by taking into account the cost of unsupplied loads and credible generation profiles.

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