Supervisory Control of Energy Distribution at Autonomous RES-powered Smart-grids using a Finite State Machine Approach*

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***Abstract*— This work addresses the issue of energy distribution between stations of an autonomous small-scale smart-grid network using a replicable and upscalable methodology that relies on a Finite State Machine (FSM) approach. The development of the FSM approach involves the modelling of all systems (nodes) of the autonomous network and the identification of the needs and the requirements for energy management in a dynamic and distributed environment where Renewable Energy Sources (RES) are used as the main source of power to the grid. Furthermore, applicability of FSM approach is a main issue, since the final objective is its online implementation to the supervisory control system that derives and supplies the operations-related actions to the involved nodes of the network relying on industrial-grade software. Some indicative results are presented that demonstrate the response of the proposed method to a smart grid network with RES and hydrogen production, usage and storage.**

I. Introduction

The issue of power distribution with a smart and adaptable way is of major concern in the existing energy networks. Therefore a major effort is performed over the last years in order to evolve the existing power grid into a smart-grid network, where the decisions will be taken having into consideration the needs and requirements of all systems or nodes involved/connected to the network [1,2]. Furthermore, various energy sources, including Renewable Energy Sources (RES) such as photovoltaic and wind generators, are present which leads to a highly dynamic environment. The utilization of RES for power generation can lead to an interesting path for meeting in a unique way the concerns over climate change and security of supply as they can promote the transition to a reliable, sustainable and competitive energy system [3]. The combination of the requirements that arise by the dynamic supply and demand in the grid, formulates a highly complex environment with a large number of design variables and the decisions for the control actions require real time data collected from devices, systems and processes [4]. Thus, the design and operation of a multi-source energy network involves numerous decisions at various levels and domains. As such systems become more interconnected and diverse, it is important to be able to design the interactions among the various components in an efficient and robust way. To address this challenge it is important to rely on an architecture that considers the dynamic behavior of the involved components [5]. Based on the National Institute of Standard and Technology (NIST) standard [6], a smart grid model includes seven domains, namely Customer, Market, Service provider, Operations, Bulk generation, Transmission, and Distribution. Each of these domains can function differently, interactively, and cooperatively. This work focuses mainly on the operations domain where the decisions are made for the overall operation of the connected nodes.

The operational objectives are to distribute energy based on a formal methodology, to maximize the usage of available stored power at network level and to maximize the utilization of the total amount of available renewable energy. The paper is organized as follows. A RES-enabled network is described at Section II. The energy decisions framework is introduced in Section III and the developed Finite State Machine approach is described at Section IV. Finally some indicative results are presented at Section V.

II. Autonomous RES-powered Smart Grid With Hydrogen Production and Usage

An existing smart-grid network was used in order to develop and study the applicability of the proposed approach with a model based technique of the existing infrastructure and will be analyzed at the subsequent sections. The autonomous smart grid involves three systems (nodes) with local battery storage capabilities, hydrogen generation and long-term hydrogen storage options. Fig. 1 illustrates the topology of the isolated RES-enabled network.

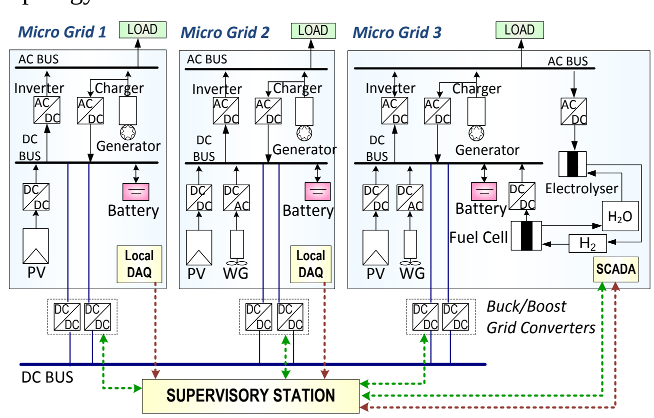

Figure 1. Architecture of the autonomous smart-grid network

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Each system, or otherwise stated station, has a PV array, wind generators and a diesel generator for backup purposes. Also one of the stations has hydrogen facilities which are comprised of a Polymer Electrolyte Membrane (PEM) fuel cell and a PEM electrolyzer for the production, utilization and storage of hydrogen [7]. This smart grid is located at Xanthi, Greece and is controlled by a SCADA (GE Proficy iFIX) system while the Machine to Machine (M2M) communication for the decision making is implemented by an Internet of Things (IoT) enabled architecture using a custom developed middleware using a light weight protocol (MQTT).

III. Energy Distribution in Networked RES-Enabled Systems

When multiple nodes exist in a network that can request energy or are able to provide energy, then an Energy Decisions Framework (EDF) is necessary in order to derive the appropriate actions for the energy distribution among the nodes [7]. The respective amount of energy that the involved node will receive or dispatch is determined by an algorithm that considers the status and other important parameters of each node. For completeness reasons only the basic aspects of the EDF is presented in this work and more details can be found at [7].

A. Energy Decision Framework

The EDF derives the decisions (Operations Domain) for the power distribution between the end users (Customer domain). It is a generic approach and does not require any specific models for the representation of the power production, load demand and power supply needs. Therefore it can be applied to different architectures and networked systems. Overall the description of the smart-grid network is described by a) a structure that defines the hierarchical connection of the systems within the network, b) the components that defines the structural and operational parameters and variables along with the relationships between the parameters, c) the limits/boundaries that set the range of the application domain and they can be different for each system and d) the behavior, that contains the status of each system (enabled or not). In this work the behavior is modeled by a Finite State Machine (FSM) and thus particular attention will be given to the logical variables which are related to the modification of the varying parameters. The sets of parameters and variables that describe the network level components are:

- $St_{const,i} = \{AGE, CP, R_{CH}, R_{DCH}\}$, where AGE is the battery aging factor, CP is its capacity, R_{CH} and R_{DCH} are the rate of charging and discharging of the batteries.
- $St_{\mathrm{mod},i} = \{Z_{r,low}, Z_{r,up}, Z_{s,low}, Z_{s,up}\}$, where Z_r determines the zone where energy is requested, Z_s is the zone where the system is able to supply energy to the network , *low* and *up* are the limits of each zone.
- $Mt_i = \{En_s, En_r, En_{ext}, SOC_{BAT}\}$, is the set of variables that are dynamically evolving and determine En_s, En_r, En_{ext} as the available, the requested and the externally supplied energy, while SOC_{BAT} is the State of Charge of the battery stack. En_{ext} is calculated by the energy management algorithm.
- $\delta_z = \{\delta_r, \delta_s, \xi_r, \xi_s\}$, is the set of Boolean variables that defines the status of the respective zone (request or supply).
- $\delta_g = \{\delta_{en}, \delta_{op}\}$, is the set of Boolean variables that defines whether the system is available to be included at the energy exchange operations (δ_{op}) and whether the system requests or supplies energy (δ_{en}).

Based on this representation a decision-making methodology is developed that rely on a FSM (Section IV) and uses a propositional-based logic. The level of energy of each battery stack defines a set of Boolean variables and each subsystem is related to one or more Boolean variables, that determines whether the subsystem is allowed to operate or not. When a system sends or requests energy its battery content is modified according to the charging/discharging rate. Fig. 2 shows how the zones are structured with respect to the SOC of each battery. Each area is assigned to a Boolean variable (δ_1,δ_2,δ_3,δ_4,δ_5). The variables δ_1,δ_2 and δ_4,δ_5 are related with the request and supply zones while variable δ_3 is related to the autonomous operation of the node and exists to avoid discontinuities and define the operation:

$$
\begin{aligned}
&[\delta_1(t)=1] \leftrightarrow [SOC_{BAT}(t) \le Z_{r,low}] \\
&[\delta_2(t)=1] \leftrightarrow [SOC_{BAT}(t) \le Z_{r,up}] \\
&[\delta_3(t)=1] \leftrightarrow [SOC_{BAT}(t) \le Z_{s,low}] \\
&[\delta_4(t)=1] \leftrightarrow [SOC_{BAT}(t) \le Z_{s,up}] \\
&[\delta_5(t)=1] \leftrightarrow [SOC_{BAT}(t) \le SOC_{\max}]
\end{aligned} \tag{1}
$$

The conditions that describe the enabling of the Boolean variables contain only the single bound validity check as the lower bound is guaranteed by the mutually exclusive conditions that the logical variables must satisfy:

$$
\begin{aligned}
&[\delta_1(t)=1] \rightarrow [\delta_2(t)=\delta_3(t)=\delta_4(t)=\delta_5(t)=1] \\
&[\delta_2(t)=1] \rightarrow [\delta_3(t)=\delta_4(t)=\delta_5(t)=1] \\
&[\delta_3(t)=1] \rightarrow [\delta_4(t)=\delta_5(t)=1] \\
&[\delta_4(t)=1] \rightarrow [\delta_5(t)=1]
\end{aligned} \tag{2}
$$

A system cannot be at the same time at two zones which is guaranteed by (2).

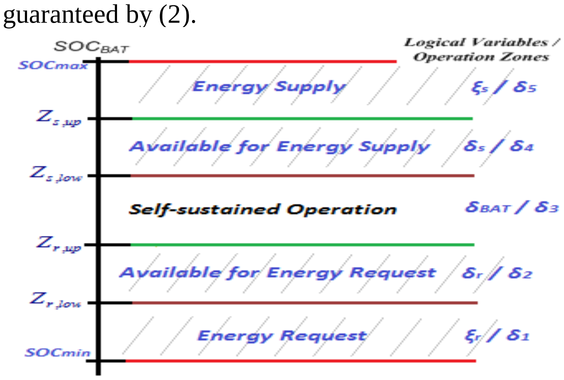

Figure 2. Relationship between the request and supply zones for the SOC of the battery stack for each system (node) of the network

The energy distribution algorithm consists of the following steps.

Algorithm 1: Centralized Energy Distribution Algorithm

Step 1: Calculate number of systems able to provide energy N_s and systems requesting energy N_r based on the status of δ_{EN}.

Step 2: Calculate the total available ($En_{tot,s}$) and requested ($En_{tot,r}$) energy at the network level from each system.

Step 3: Calculate the amount of energy for each system requesting energy (En_{fr})
Step 4: Calculate the amount of energy to receive by or to provide by each system (En_{ext})
Step 4a: In case the fraction of the available energy for node i is $En_{fr,i} \leq R_{CH_i} \cdot t$, then the energy that node i receives is $En_{fr,i}$ where t is time in hours.
Step 4b: Otherwise the energy that node i receives is $R_{CH,i} \cdot t$ and the energy in this case that node k provides to node i is given by $E_{s_{k,i}}$
Step 5: Send the calculated energy settings to the subsystems

where

$$En_{fr,i} = \frac{En_{tot,s} \cdot \delta_{r_i} \cdot R_{CH_i} \cdot t}{En_{tot,r}} \tag{3}$$

$$En_{tot,r} = \sum_{j=1}^{3} \delta_{r_j} \cdot R_{CH_j} \cdot t \tag{4}$$

$$En_{tot,s} = \sum_{j=1}^{3} \delta_{s_j} \cdot R_{DCH_j} \cdot t \tag{5}$$

$$E_{s_{k,i}} = \frac{\delta_{s_k} \cdot R_{DCH_k} \cdot t \cdot \delta_{r_i} \cdot R_{CH_i} \cdot t}{En_{tot,s}} \tag{6}$$

When the external energy (En_{ext}) is positive then the system receives energy, whereas when it is negative the system provides energy to the grid. Algorithm 1 takes into consideration all the parameters as defined for each system. Also it is assumed that the total amount of the provided energy based on the discharge rate can be received by the systems of the network. Algorithm 1 is used as a proof of concept for the determination of the amount of energy that can be distributed for each node of the isolated smart-grid network.

IV. FINITE STATE MACHINE

In this work a FSM is used to describe the evolution of the status of each node related to the energy exchange in the smart-grid network. More specifically, a FSM can be applied for the study of the behavior of the autonomous network due to its inherent hybrid structure [8]. In general, a FSM is a dynamic approach that describes the evolution in time of a set of discrete and continuous state variables. A FSM A is a tuple $A = \{Q, X, \delta, I, Y, \lambda\}$ where Q is a set with all possible states of the machine, X is the input alphabet of A, δ is the state transfer function of A, I is the set of initial states of A, Y is the output alphabet and λ is the output function of the machine A. The following apply for the machine A:

$$\begin{aligned} &\delta : Q \times X \to Q \\ &\lambda : Q \times X \to Y \end{aligned} \tag{7}$$

where

$$q \xrightarrow{x/y} q' \Leftrightarrow \begin{cases} \delta(q,x) = q' \\ \lambda(q,x) = y \end{cases}, \quad x \in X, \quad y \in Y \tag{8}$$

The FSM for each node in the aforementioned smart-grid network consists of seven states $Q = \{q_0, q_1, q_2, q_3, q_4, q_5, q_6\}$, with $I = \{q_0, q_2, q_4, q_5, q_6\}$, where:

q_0: isolated operation state
q_1: supply energy after $Z_{s,up}$ has been reached (upwards)
q_2: supply energy
q_3: receive energy after $Z_{r,low}$ has been exceeded (downwards)
q_4: receive energy
q_5: available for energy supply (without supplying)
q_6: request energy (without receiving)

A five letter input alphabet $X = \{x_1, x_2, x_3, x_4, x_5\}$ is applied where:

$$\begin{aligned} &x_1 : \delta_r = 0 \wedge \delta_s = 0 \\ &x_2 : \xi_s = 1 \\ &x_3 : \delta_r = 0 \wedge \delta_s = 1 \wedge \xi_s = 0 \\ &x_4 : \xi_r = 1 \\ &x_5 : \delta_r = 1 \wedge \delta_s = 0 \wedge \xi_r = 0 \end{aligned} \tag{9}$$

The Boolean variables are evaluated as:

$$\begin{aligned} &\delta_r = 1 \Leftrightarrow SOC_{acc} \leq Z_{r,up} \\ &\delta_s = 1 \Leftrightarrow SOC_{acc} \geq Z_{s,low} \\ &\xi_r = 1 \Leftrightarrow SOC_{acc} \leq Z_{r,low} \\ &\xi_s = 1 \Leftrightarrow SOC_{acc} \geq Z_{s,up} \end{aligned} \tag{10}$$

Finally a three letter output alphabet $Y = \{-1, 0, 1\}$ is applied where:

-1 : the node requests power
0 : isolated operation of the node
1 : the node can supply power

A power production node cannot supply and request energy at the same time. So the following restrictions for the logical variables $\delta_r, \delta_s, \xi_r, \xi_s$ apply

$$\begin{aligned} &\delta_r \wedge \delta_s = 0 \\ &\xi_r \wedge \xi_s = 0 \\ &\xi_s = 1 \Rightarrow \delta_s = 1 \\ &\xi_r = 1 \Rightarrow \delta_r = 1 \end{aligned} \tag{11}$$

The state transfer function δ and the output function λ are given at Tables I and II respectively.

TABLE I. FSM MOVEMENT TABLE FOR TRANSFER FUNCTION

δ	x_1	x_2	x_3	x_4	x_5
q_0	q_0	∅	q_5	∅	q_6
q_1	q_0	q_2	q_1	∅	∅
q_2	∅	q_2	q_1	∅	∅
q_3	q_0	∅	∅	q_4	q_3
q_4	∅	∅	∅	q_4	q_3
q_5	q_0	q_2	q_5	∅	∅
q_6	q_0	∅	∅	q_4	q_6

TABLE II. FSM OUTPUT TABLE FOR OUTPUT FUNCTION

λ	x_1	x_2	x_3	x_4	x_5
q_0	0	∅	0	∅	0
q_1	0	1	1	∅	∅
q_2	∅	1	1	∅	∅
q_3	0	∅	∅	-1	-1
q_4	∅	∅	∅	-1	-1
q_5	0	1	0	∅	∅
q_6	0	∅	∅	-1	0

The FSM that describes the change of states for the nodes of the smart-grid network is shown at Fig 3.

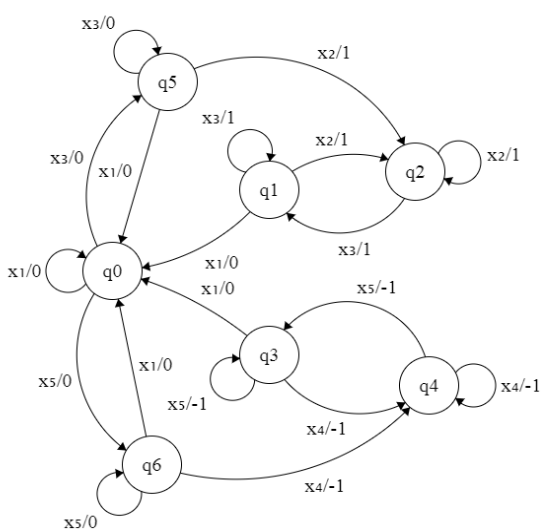

Figure 3. Finite state machine for each node

Overall the proposed FSM is able to incorporate engineering and computational knowledge and it can incorporate various operating modes.

V. Operation Analysis and Behavior Assessment

The operation of the nodes within the network is explored using the aforementioned EDF with the FSM. At first an operation scenario based on EDF implementation is compared with the case without it in order to demonstrate the added value of the energy exchange between the nodes and showing the benefits of the developed EDF. The scenario presents a seven day operation of the autonomous network. Fig. 4 shows the evolution of the battery SOC for each node in the case where the EDF is not enabled and thus no energy transfer among the nodes may be applied.

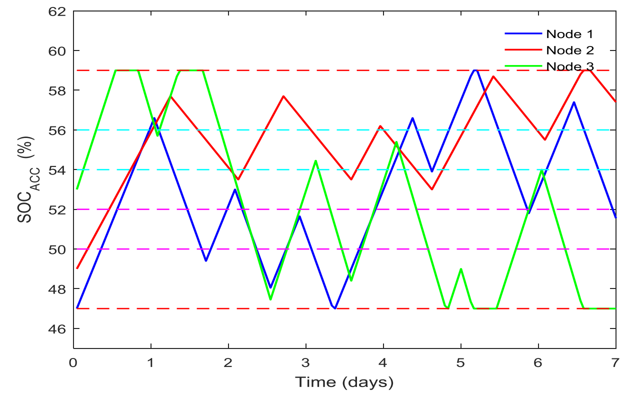

Figure 4. Battery status of the three nodes for 7 days without EDF enabled

According to the scenario the initial value of the SOC of battery stack at each system is at a different level and the charging/discharging rate of each battery is different following its specifications. The upper and lower bounds (presented by the dashed lines) of the request/supply zones are the same and there is always a load to be fulfilled.

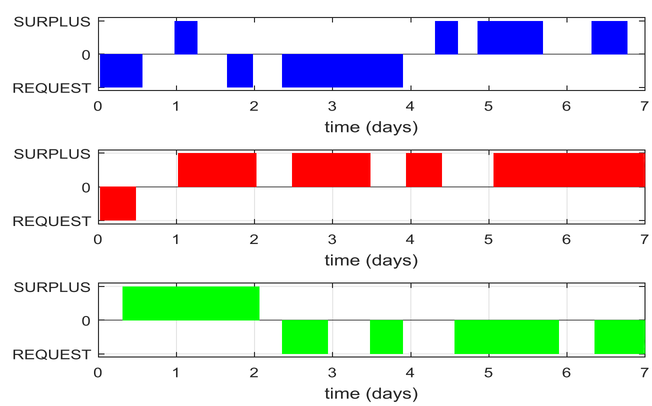

Figure 5. Availability for energy exchange on each node without EDF enabled. (a) node 1, (b) node 2, (c) node 3

Fig. 5 shows the availability periods for energy exchange when the EDF is not applied while Fig. 6 shows the corresponding availability periods when the EDF is applied.

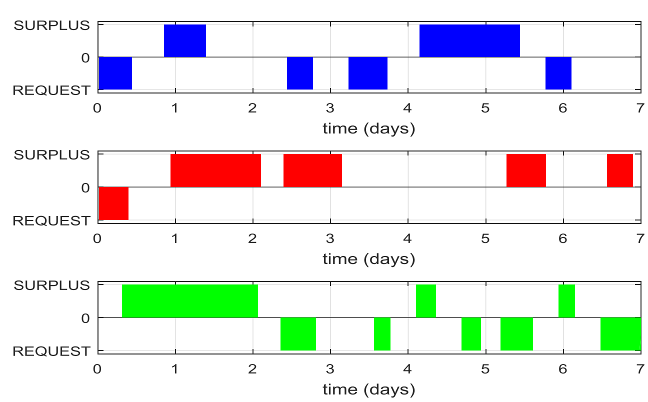

Figure 6. Availability for energy exchange on each node with EDF enabled. (a) node 1, (b) node 2, (c) node 3

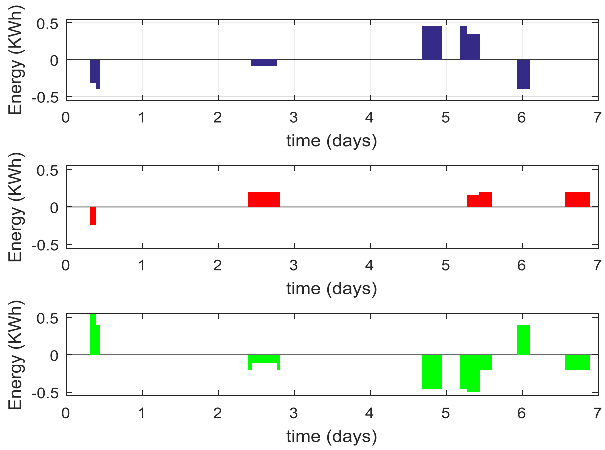

Figure 7. Energy exchange among the nodes when EDF is applied.

The amount of energy that each node supplies or receives following the supervisory control actions according to EDF is shown in Fig. 7. Fig. 8 presents the evolution of the SOC of each battery stack during the simulation period of seven days in comparison to the corresponding battery SOC without involving the EDF and thus without energy exchange.

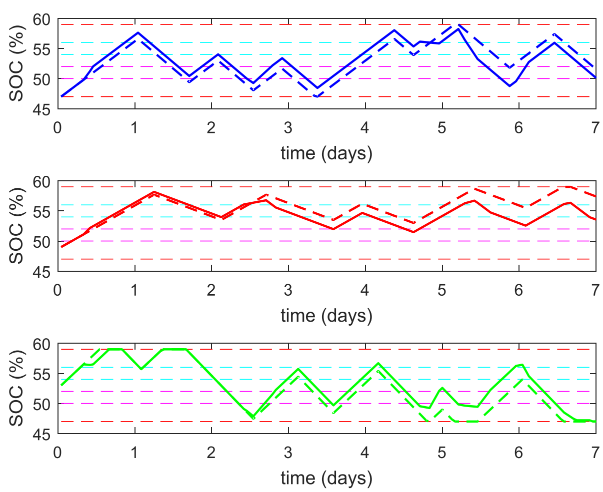

Figure 8. State of charge of the three nodes for 7 days. –EDF enabled, --EDF disabled. (a) node 1 SOC, (b) node 2 SOC, (c) node 3 SOC

The predefined limits of the battery SOC in the simulation are 47% minimum and 59% maximum. In case of energy surplus the excess energy is wasted if the battery SOC is above 59% and in case of energy deficit the auxiliary power systems operate to meet the load if the battery SOC is below 47%.

With the EDF enabled the SOC of each battery remains longer in the autonomous operation zone of the respective node compared to the case of operation without EDF. This results in the reduction of the time period that each battery stack operates in its predefined limits and in an increment of the time of autonomous operation of each node. Moreover the rate of utilization of the produced energy (RES) is increased and consequently the energy required from the auxiliary power systems i.e. Fuel Cell (node 3) and/or diesel generator is less and thus the usage of fossil fuel is accordingly affected.

TABLE III. ENERGY EXCESS-SHORTAGE PERIODS

	Periods of Energy excess (unused energy) (hours)		**Auxiliary power systems operation (hours)**	
	EDF ON	EDF OFF	EDF ON	EDF OFF
Node 1	0	2	0	1
Node 2	0	3	0	0
Node 3	13	16	8	21
Total	13	21	8	22

Table III shows a comparison of the time periods in which the nodes do not use the available energy and the periods of operation of the auxiliary power systems due to SOC limitations. A 38.1% reduction is noted in the time periods where there is excess energy that is wasted as well as a 63.6% reduction in the usage of auxiliary power systems.

According to the above Fig. 9 shows the overall supplied and respectively the received energy for each of the three nodes for the period of seven days.

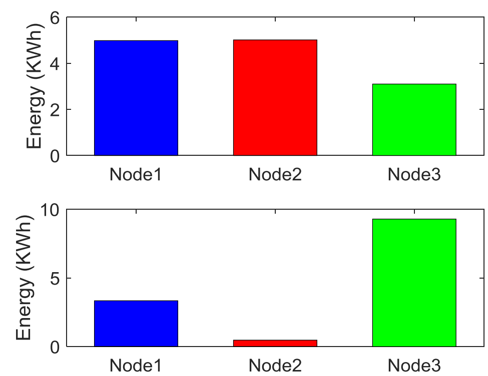

Figure 9. Balance of distributed energy with EDF enabled. (a) total energy supplied from each node, (b) total energy received from each node

TABLE IV. AVAILABILITY OF ENERGY EXCHANGE

	Energy Supply Availability (hours)		**Energy Request (hours)**		**Isolated Operation (hours)**	
	EDF ON	EDF OFF	EDF ON	EDF OFF	EDF ON	EDF OFF
Node 1	44	45	38	58	86	65
Node 2	66	106	9	11	93	51
Node 3	53	42	45	72	70	54
Total	163	193	92	141	249	170

Table IV shows a comparison of the periods in which the three nodes were available of supplying-requesting energy and operate autonomously. Totally it is noted a 15.54% reduction in energy supply availability, a 34.75% reduction in energy request and a 46.47% increment in isolated operation. Consequently the operational objectives which are to maximize the usage of available stored electrical energy at network level, to maximize the utilization of the total amount of available renewable energy and to use less external energy were approached much better using EDF.

VI. CONCLUSION

The aforementioned work has presented a formal methodology based on a flexible approach for the energy distribution among the nodes of a small-scale autonomous smart-grid. The EDF derives the decisions using a finite state machine in conjunction with propositional based reasoning. The implementation of optimization based techniques with the aforementioned EDF is currently under study. As this is a generic approach it can be implemented to the supervisory node of the operations domain of the network, where a Supervisory Control and Data Acquisition (SCADA) system is usually present. Alternatively due to the nature of the FSM, such approach can be implemented to PLCs as well. Overall the scalability of the method in autonomous systems with a larger number of nodes and the potential for future incorporation of other variables in the decision making process makes it a good candidate for demonstration purposes to actual systems.

REFERENCES

[1] C. Ziogou, D. Ipsakis, C. Elmasides, F. Stergiopoulos, S. Papadopoulou, P. Seferlis, S. Voutetakis. "Automation infrastructure and operation control strategy in a stand-alone power system based on renewable energy sources". Journal of Power Sources, 196 (2011) No. 22, pp. 9488-9499.

[2] M. Zachar, P. Daoutidis. "Microgrid/Macrogrid Energy Exchange: A Novel Market Structure and Stochastic Scheduling". IEEE Transactions on Smart Grid. Vol. 8, Issue: 1, Jan. 2017

[3] Lund, H., Andersen, A. N., Østergaard, P. A., Mathiesen, B. V., Connolly, D. (2012). "From electricity smart grids to smart energy systems–a market operation based approach and understanding". Energy, 42(1), 96-102.

[4] S. Sharma, A. Dua, S. Prakash, N. Kumar, M. Singh, "A novel central energy management system for smart grid integrated with renewable energy and electric vehicles", 2015 IEEE International Transportation Electrification Conference (ITEC), Chennai, 2015, pp. 1-6.

[5] H. Al Haj Hassan, A. Pelov, L. Nuaymi, "Integrating Cellular Networks, Smart Grid, and Renewable Energy: Analysis, Architecture, and Challenges", IEEE Access, 3, 2015, pp. 2755-2770.

[6] NIST, "NIST framework and roadmap for smart grid interoperability standards, release 3.0," National Institute of Standards and Technology, Gaithersburg, MD, Special Publication 1108R3, Sept. 2014.

[7] C. Ziogou, S. Voutetakis, S. Papadopoulou, IEEE 23rd International Conference on Telecommunications, ICT 2016, 2016, art. no. 7500384, 1-5.

[8] C. Ziogou, D. Ipsakis, P. Seferlis, S. Bezergianni, S. Papadopoulou, S. Voutetakis S, "Optimal production of renewable hydrogen based on an efficient energy management strategy", Energy, 55, 2013, pp. 58-67.