A Multi-Agent System for Solar Driven DC Microgrid

Diana Rwegasira[1 2], Imed Ben Dhaou[3 5], Aron Kondoro[1 2], Naiman Shililiandumi[2], Amleset Kelati[1 4], Nerey Mvungi[2], Hannu Tenhunen[1 4].

[1] KTH Royal Institute of Technology in Stockholm (SWEDEN)
[2] University of Dar es Salaam (TANZANIA)
[3] College of Engineering, Qassim University (SAUDI ARABIA)
[4]University of Turku (FINLAND)
[5]University of Monastir (TUNISIA)
dianasr@kth.se, phd.imed.bendhaou@ieee.org, kondoro@kth.se, smakere@gmail.com, smleset@kth.se, nhmvungi@udsm.ac.tz, hannu@kth.se

***Abstract*— This paper proposes a Multi-Agent System (MAS) modeling and control architecture for a solar driven DC microgrid. The microgrid consists of solar system as a source of power, energy storage system, critical and non-critical houses (loads) with their own solar and storage as well. For the proposed MAS an individual house can have the ability to sell extra power to the main solar source. The main solar source can generate power and provide to the community when needed. The MAS also controls and monitors an automatic load shedding technique to disconnect non critical loads when there is a deficiency of power supply to the system. The validity of the objectives are demonstrated by agent based system which runs under REPAST simulation tool which used successfully three loads: hospital and two houses during simulation.**

Keywords—Multi Agent, Microgrid, SCADA systems

I. INTRODUCTION

Electric utility provides the growth and development of vital sectors in the society that needs to be properly managed. In the management of distributed energy systems, agent based system has been a successful candidate to solve complex and distributed control problems. Its importance in cooperating system during normal and emergency situations has led to proper utilization of smart microgrid control [1]. Research done by [2],[3] showed that the trends on monitoring and controlling the operation of electric power systems are moving from SCADA system to the use a multi-agent system. Multi agent system is the combination of different agents working together to perform a certain tasks. The significant factor of multi agent systems in the electric power grid is the resiliency and autonomous re-configuration behaviors. The success of the use of multi agent systems has been also explained in [3]. Multi agent systems can be applied in different sectors such as e-health, transportation, e-commerce, network monitoring, distributed artificial intelligent and infrastructure. One such application of multi agent systems was in the simulation of emergency medical services in London hospitals [4].

The main components of agent based control for microgrid are: energy source unit, energy storage unit, load, energy source agent, energy storage agent, HMI (Human Machine Interface) and load agent [5]. Agent based control has several advantages such as modularity, decentralization, autonomous reactive, proactive, scalability and re-usability of the system.

Microgrid has gained ample attention due to the technological potential increase of power system efficiency and security. It is a system that contains distributed energy resources, loads and the associated control and management units. Microgrid can work on islanded or grid-connected modes and spans a small area as compared to the grid [6]

Multi agent systems are normally applicable in both centralized and decentralized control systems. The use of agents provide a tool for intelligent decisions and proper management of the systems in terms of self-healing and fault tolerance [7],[8]. Different platforms have been introduced for the development and implementation of agent based systems such as JADE, ZEUS, VOLTTRON and REPAST Simphony. In this work, REPAST runs in Java is used for development and simulation as it provides scalability and interoperability features.

Many researchers have worked with regards to DC microgrid to achieve several factors based on smart grid systems. Most published techniques focused on one of the following issues: power optimization, cost minimization and load shedding at the consumer premises. The research done by Farooq et al. in [9] proposed a model for DC microgrid using PV as source of power that can later be integrated to the main electric grid. The work focused on sharing of extra power among the consumers. It did not consider load shedding strategies. Also, the authors used MATLAB tool for simulation. Manisa et al. in [10] designed a multi agent system with secure critical loads using PV systems. The work focused on external fault detections, secure loads and resynchronization of microgrid to the main grid after fault clearance. However, their developed agents lack autonomy as the system requires a control agent.

Mohammed et al. in [11] used a micro-CHP (Combined Heat and Power) to generate DC power for microgrid. The experiment done was based on load shifting technique. The

978-1-5386-1667-3/17/$31.00 ©2017 IEEE

load/house is equipped with a smart meter and controllable devices. However, the authors did not use agents to achieve its objectives. Taesic et al. in [12] proposed the model for a residential DC microgrid using PV system and smart homes. The work addressed the solution using agent based systems and REPAST simphony as a simulation tool. However, their work did not focus on load shedding technique. Also, Marko in [13] developed a stochastic model predictive control for optimal economic operation in a residential DC microgrid. The authors used PV arrays for power sources, battery stack and fuel stack to optimize the power flow. They also used the linear programming approach to model their work.

This paper presents a multi agent system for solar driven DC microgrid. Section II describes our DC microgrid model. The description of the multi-agent system for load shedding and extra power selling is elaborated in Section III. Section IV reports the simulation results. Finally, Section V concludes our paper.

II. DC MICROGRID

Renewable energy has emerged as solutions to provide electricity to remote locations that have no access to main grid, to reduce carbon dioxide, to increase the efficiency of the utility grid, etc. The use of renewable technologies such as solar power and wind power has proven to be cheaper alternative at household level. DC microgrid systems focused on: (i) increasing power production, (ii) reducing energy dissipation and (iii) decreasing facility cost. DC microgrid systems are also vital during disaster as they can operate in islanded mode. DC microgrid possesses various features which makes it very attractive. Some features of the DC microgrid are: (i) there is no need for synchronization between different sections of the network (ii) has virtually zero energy loss that occur when converting DC voltage into AC, (iii) operates at low cost, (iv) resilient to skin effect and inductive/capacitive loss thus requires less regulation compared with AC grid systems and (v) enables the connection of DC devices that have high efficiencies compared with AC appliances.

The use of the multi agent system in the provision of smart control, monitoring and management is of more value in many societies. Many researchers have shown much interest with DC microgrid systems due to its features such as scalability, proactive, sociability, adaptive and security. Recently, control and monitoring of DC microgrid systems have moved to the use of multi agent systems which replaced the SCADA (Supervisory Control and Data Acquisition). The main feature of multi agent systems is its capability to work in both decentralized and centralized manner compared to SCADA which rely only in centralized way.

A. Modelling of DC Microgrid for Residential Houses

The DC microgrid system for residential houses normally includes generation, distribution and storage of DC energy. The microgrid consists of solar PV panels as a generation point, a battery for storage and the loads/houses for consuming power as seen in Fig.1. The set-up of the DC microgrid is presented by agents which are: solar power agent, storage agent and load agent. The DC houses have appliances that operate in DC mode.

In DC microgrid, using agent based system, all agents will work in a decentralized manner, whereby each agent will be able to make its own decision. The solar agent will supply energy to load agents which are categorized as critical load (a hospital) and non-critical (two individual houses). The task of solar agent is to charge the battery until it is full before starting to supply to the loads. This is also done by each individual load having its own solar panel and storage for consumption purposes.

With respect to automatic load shedding technique, the main grid will automatically disconnect all non-critical loads and leave critical load running. In this case, always the focus is on supplying the critical load before considering distributing to other loads. The storage units will supply the load with the necessary energy in case PV cells fail to generate enough power during a rainy day, in the evening, etc. Furthermore, an individual house can sell extra power to the grid after charging its own battery and be assured that the power it has is enough to supply for the next twenty four hours. The payment process can be done using advanced analytics.

The motivation behind this modeling is to produce the results which can be used in a real system that runs in a renewable energy platform. The automatic load shedding techniques use solar as a main source of energy and each individual house has an autonomous energy generation system. The house owner can act as a consumer and producer of the energy. Extra power generated by individual house can be sold to the main grid to cover the energy needs.

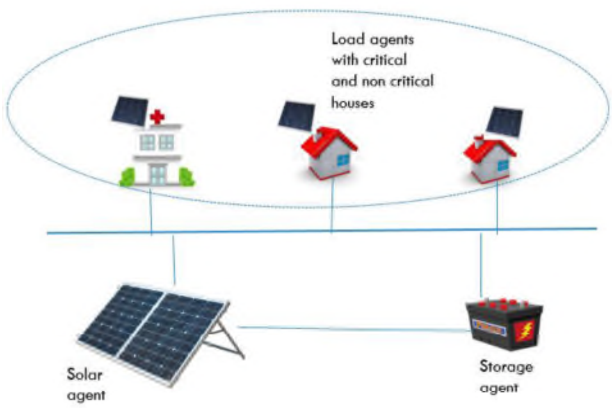

Figure 1: Agent Based Solar DC microgrid Set-up

B. Agent based Simulation Environment

In order to model the power system and evaluate the multi-agent based control algorithm a simulation environment based on REPAST was used. REPAST Symphony is a Java based toolkit that provides different tools such as Java, Logo, Groovy and State charts, for developing multi-agent based models [15]. REPAST is a mature open source tool that allows easily design and simulates dynamic systems that involve multiple interacting agents.

REPAST has already been used to model and simulate different applications and use cases in the electric power domain. It has been used to model and simulate the interaction of smart homes with distributed power generation in order to minimize individual power costs and peak power consumption [16]. It has also been used to simulate very complex and dynamic distributed electricity markets in smart grid scenarios where customers with competing goals and constraints buy and sell electricity to each other with dynamic prices [17]. As such, REPAST is a powerful tool with a proven track record to provide a useful simulation environment for the scenario presented in this paper.

III. MULTI-AGENT SYSTEM FOR DC MICROGRID

In this section, we are going to describe the role of the three agents that will be used to implement the load shedding challenge and selling extra power from individual load to the main solar source. Table 1 shows the algorithm used by all agents with all activates on it.

A. *Main Solar Power Agent(Supplier)*

This is the main source of power. Its attributes upon getting total power required in the system are:

- Battery capacity, B in Volts.
- The power consumption of each load per 24hours (in Watt).
- The average power that a single solar panel can generate (in Watt).
- The average solar energy per day, S (In our model, we considered that the solar panels accumulate power for 8 hours per day as per reference in [14] explaining about the solar profiling in Tanzania.)

In this case, the total energy demand is calculated using (1:

$P = \sum_{k=1}^{3} W_k$ (1), where W_k is the power demand for the k^{th} load (the hospital or a house).

Also with respect to domain knowledge, the solar agent must:

- have the power consumption of each load to supply (W_k),
- be able to charge the battery, and
- be able to automatically perform load shedding.

Buying or selling energy on different load agents upon request is another task for the solar agent. In the selling scenario, any load can sell to solar agent without any priority, but in the buying scenario, when two or more load agents request power, the solar agent needs to consider the amount of power for each load agent and what information it has on its database with respect to power consumption.

B. *Storage Agent*

It is the agent which stores power after it has been charged by solar panels. The task of this agent is to monitor charging and discharging activities, to provide power when the solar agent has a power deficiency to supply to individual load. The provision of power should be done autonomously when the solar agent has power deficiency to supply its consumers. In this case, the storage agent has to pick up and when the solar agent starts to gain the sunshine and absorb energy the storage agent needs to retain the power.

The battery will be operating at its maximum and minimum value using the equation (2):

$$30\ \% <= \text{State of Charge} >= 80\% \quad (2)$$

C. *Load Agent(Consumer)*

This agent has several attributes. The load agent has a critical load and non-critical loads. For critical load, the solar agent needs to supply the power to it all the time. The non-critical load is the subject of load shedding technique and will be disconnected from the grid in case the demand in energy is higher than the supply. Furthermore, each load agent has its own solar panel and battery storage unit as a back-up source of energy and for cost optimization process. When load shedding occurs, the non-critical load can decide to use its own solar power to provide DC power to its own appliances.

Moreover, each load agent can sell extra power to the solar agent as the main provider of the power. In this case, solar agent can generate more energy from different sources rather than depending only on sunshine. The pricing issues between the two parties (load and solar agents) can be negotiated as a term and references before the action starts.

Load profiling is an essential tool for the establishment of advanced control and monitoring algorithms. In this work, the load profiling data was obtained from the utility company Tanzania electrical and supply company (TANESCO) for three customers (a hospital and two individual houses). As seen in Fig.2, the power consumption for the hospital is maximum peaks to 23Kwh per day and two normal loads are 5Kwh and 1Kwh respectively. This means that the main microgrid will have to consider the total power by summing up the maximum power for each load. The consumption of the load will be in a distribution form as in Fig.2.

IV. RESULTS AND DISCUSSION

A. *Context in the REPAST platform*

The aim of the experiment was to perform load shedding challenge and also allow extra power to be sold to other households in the microgrid. REPAST Simphony which runs in Java was the tool used to develop and demonstrate the context hence obtain the results. Table 2 Shows the main attributes of our agent on implementations.

The operations of the solar agent are generating, storing and distributing power to load agents. This is done while ensuring the priority to critical loads that are served with guaranteed power. Load agent operations also include generating and storing power for their own use while selling power to the solar when they have excess power generated.

Table 1: Algorithm for Solar, Storage and Load Agents

	Solar	Storage (Battery)	Critical Load	Non-Critical Load
Data	-Total power of it (P_s) Constant power of each load required -Power consumption of each load at time t -Storage capacity to charge	-State of charge (SOC) of the battery, -Constant power of each load required -Power consumption of each load at time t	-Power used by the load at time t, i.e. its load profile -Its solar and batter charge capacity	-Power used by the load at time t, i.e. its load profile -Its Solar and battery charge capacity
Action	-Provide power to the loads -Charge the main battery -Perform load shedding Buy/sell the power to the load	Act as a backup of main solar to provide power to the loads	-Charge its own battery -Get power from main solar -No cut off power	-Charge its own battery -Get power from main solar -Cut off may take place
Rules1	$P_s > P_{threshold}$ (Threshold power)	SOC battery>= 30%	Switch ON	Switch ON
	$P_s < P_{threshold}$	SOC battery>= 30%	Switch ON	Isolate from solar, get from main storage
	$P_s < P_{threshold}$	SOC battery<= 30%	Switch ON	Isolate from storage, get from its own source.
Rules 2 Buy/sell	Get from Non critical loads extra power	-	-	Supply extra power to the main solar
Return and end	P_S, Power $_{of\ each\ load,}$ Total $_{extra\ power}$ in Kwh	SoC in Percentage of Kwh	$Power_{critical,}$ in KWh	$Power_{noncritical,}$ $Power_{solarNonCriload,}$ $Power_{extra}$ in Kwh

Table 2: Attributes of Agents

Attributes	Agent		
	Solar	**Storage**	**Load**
Time	Yes	Yes	Yes
Sunshine	Yes	No	No
Power controller	Yes	No	No
Storage capacity	Yes	Yes	No
Load consumption	Yes	Yes	Yes

There are two methods which are: *run* and *distributePower* in the solar agent. The *run* method is the one which is called on every time simulation unit of simulation and is preceded by the annotation of @ScheduleMethod. This is the same for the load agent class which has the same functionality. The *distributedPower* is the method for distributing power with respect to the consumption at the time t. The context of the model is presented with the class SPEContextBuilder which implements the *ContextBuilder class* of the REPAST symphony framework. During the creation of simulation context which is taking place at the build method of *class SPEContextBuilder*, one instance of *SolarPowerSupplier class* is created with all of its attributes which serves as Solar agent. Also, during the context building, three instances of *class SolarPowerConsumer* are created as load agents with all of its attributes.

Each instance of *SolarPowerConsumer class* is running with its own raw data containing power consumption at different times of the day. This represents different power consumption and the behavior of the consumer on a daily basis. During program execution, on each time tick there is an increment of one hour in load and solar agent for better visualization and conceptualization. This change in time will call for the different power output of load and solar agent.

Prioritization is done on the *distributePower* method of *SolarPowerSupplier class* which first checks the storage level of the storage agent to ensure it has enough power to serve the critical load for the next 12 hours and the surplus power will be distributed to all consumers. Otherwise power will be supplied to the critical load only. Extra power is checked by the method *getExcessPower* of *SolarPowerConsumer class* which first checks the consumer own storage level and power available to the loads. In case the storage unit is full and *loadPower* is producing enough electricity, the surplus energy is treated as an excess power and is sold to solar agent. The run time of the results was done on the interval of 100 ticks.

B. *Simulation Results*

The results in Fig.2 show the actual power used by each customer for the selected period of time. The critical load is the one with the highest power consumption.

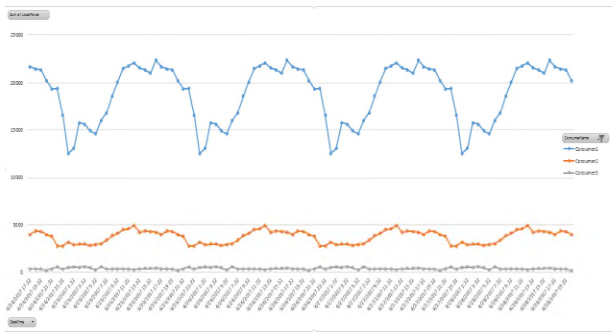

Figure 2: Real Customer power

The results of Fig.3 and Fig.4 are important in the load shedding experiment. There are different values obtained from both figures which have to be linked so as to get the meaning.

The green curve in Fig.3 shows the maximum power required by the main solar power to provide to loads. At the beginning of the run time, it can be seen that solar agent does not have enough power to charge the storage (seen with blue line) and supply to load agents. During sunrise, the solar agent begins to charge the storage and this can be seen in Fig.4. When the storage reaches its maximum value (80% SoC), then solar agent starts to supply to its loads by considering if it is enough for all loads or only for critical load. At the time equal to 17h, the grid power supplied was not enough to feed all loads and hence manage to provide to critical load only. At time 22, the power supplied was enough to supply to all loads. Load shedding was also done at 36-42h, 62-64h and 86-87 time intervals.

The storage agent curve in Fig.4 shows how the storage can accommodate the loads during night hours or when the solar agent do not have enough power to serve. The curve seems to stabilize on the second cycle the charging capacity of the storage was also stable and the consumption was enough to supply for the loads.

The excess power which was sold by individual loads can be seen as an aggregate power curve drawn with the light green line curve. In this manner, the load agent was able to save its own power and sell extra power to the solar agent.

Figure 3: Solar agent Curve

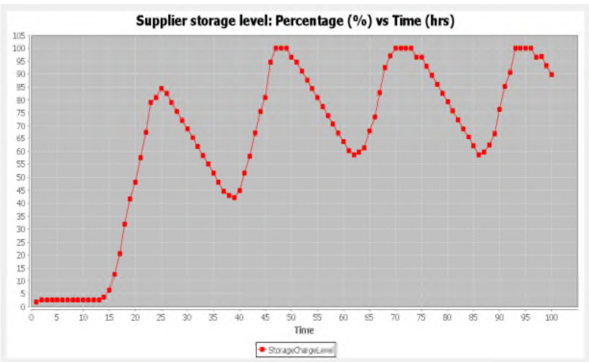

Figure 4: Storage Agent Curve

Fig. 5 shows the results of the individual solar power produced by each load agent when it has charged its battery and the power consumption of its appliances is enough for the 100 time interval. When the power reduced to zero, this means the power was utilized by the respective load agent.

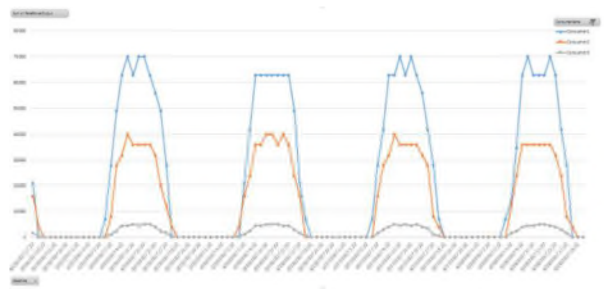

Figure 5: Individual load Agent

Results in Fig.6 show the load shedding process. At the beginning it can been seen that, the solar does not have power at all. In this case, it failed to supply to all loads. This led to even fail to charge the battery. This might be due to weather conditions. But when the solar starts to gain the power intensity, it begun by providing to the critical load and later to all loads.

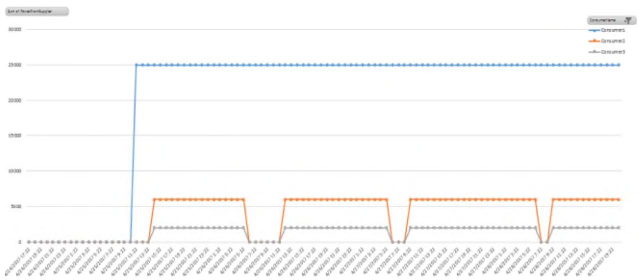

Figure 6: Load Shedding from Main Supply Solar Agent

Fig.7 and Fig. 8 explain about the excess power from each load agent and the aggregate of power sold to the main solar respectively. The total power generated can be used for consumption purposes on the loads which have no capacity of generating its own power.

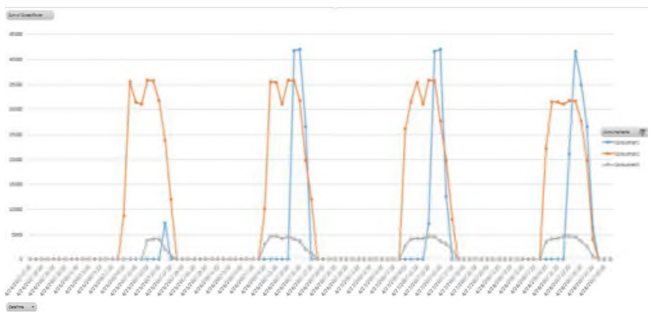

Figure 7: Excess power from Individual Load Agent

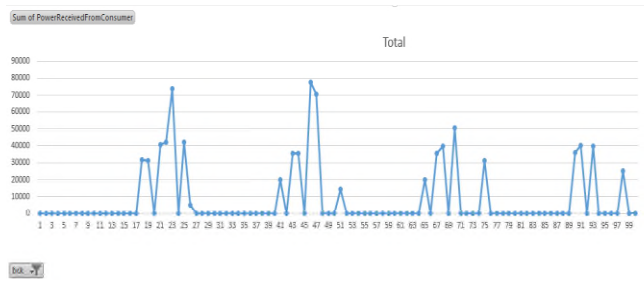

Figure 8: Extra Power Received by Solar Agent

V. Conclusion

In this paper, we proposed a multi-agent system for the control of a DC-microgrid. The system enables both load shedding and energy trading. Three agents have been defined: a solar agent for microgrid energy management, a storage agent to monitor the amount of energy available at the battery, and a load agent to connect/ disconnect the load from the microgrid and to sell the unused power. We used REPAST to implement the proposed system. A proof of concept using three loads, one critical and two non-critical loads has been demonstrated.

Acknowledgment

This work is supported by the Swedish government through the SIDA project. The authors thank the TANESCO for the support on the provision of customer data to validate our results also the Sci-Gaia project team, Prof. Simon J.E. Taylor and Dr. Anastasia Anagnostou for their contribution on the agent based system modelling and simulations.

References

[1] C. M. Colson and M. H. Nehrir, "Agent-based power management of microgrids including renewable energy power generation," in *IEEE Power and Energy Society General Meeting*, 2011, pp. 1–3.

[2] K. Manickavasagam, M.Nithya, K.Priya, J.Shruthi, S.Krishnan, S.Misra and S.Manikandan, "Control of Distributed Generator and Smart Grid using Multi-agent System," in *1st International Conference on Electrical Energy Systems, ICEES*, 2011, pp. 212–217.

[3] A. Kantamneni, L. E. Brown, G. Parker, and W. W. Weaver, "Survey of multi-agent systems for microgrid control," *Eng. Appl. Artif. Intell.*, vol. 45, pp. 192–203, 2015.

[4] A. Anagnostou, A. Nouman, and S. J. E. Taylor, "Distributed hybrid agent-based discrete event emergency medical services simulation," *Proc. 2013 Winter Simul. Conf. - Simul. Mak. Decis. a Complex World, WSC 2013*, pp. 1625–1636, 2013.

[5] G. H. Merabet, M.Essaaidi,H.Talei, M.R.Abid,N.Khalil,M.Madkour and D.Benhaddou , "Applications of Multi-Agent Systems in Smart Grids : A survey," in *International Conference on Multimedia Computing and Systems (ICMCS)*, 2014, pp. 1088–1094.

[6] N. Hatziargyriou, H. Asano, R. Iravani, and C. Marnay, "Microgrids," *IEEE Power Energy Mag.*, vol. 5, no. 4, pp. 78–94, 2007.

[7] X. Dou , X. Quan , Z.Wu , M. Hu , K.Yang, J. Yuan and M. Wang "Hybrid multi-agent control in microgrids: Framework, models and implementations based on IEC 61850," *Energies*, vol. 8, no. 1, pp. 31–58, 2015.

[8] G. Jeon, J. Park, and Y. B. Kim, "Agent Based Smart Grid Modelling," in *Winter Simulation Conference*, 2015, pp. 3114–3115.

[9] N. A. Farooq, Rabiya; Mateen, Laeeq; Ahmad, Massab; Akbar, Syeda Q.; Khan, Hassan A.; Zaffar, "SMART DC MICROGRIDS : Modeling and Power Flow analysis of a DC Microgrid for off-grid and weak-grid connected communities communities," in *Power and Energy Engineering Conference (APPEEC), 2014 IEEE PES Asia-Pasific*, 2014, pp. 173–178.

[10] M. Pipattanasomporn, H. Feroze, and S. Rahman, "Securing critical loads in a PV-based microgrid with a multi-agent system," *Renew. Energy*, vol. 39, no. 1, pp. 166–174, 2012.

[11] M. Tasdighi, H. Ghasemi, and A. Rahimi-Kian, "Residential Microgrid Scheduling Based on Smart Meters Data and Temperature Dependent Thermal Load Modeling," *IEEE Trans. Smart Grid*, vol. Early Acce, no. 1, pp. 1–9, 2013.

[12] T. Kim, J. Yun, and W. Qiao, "A MultiAgent System for Microgrids for Residential DC Microgrids," in *Power & Energy Society General Meeting, 2015 IEEE*, 2015, pp. 1–4.

[13] M. Gulin, "Control of a DC Microgrid," University of Zagreb, 2014.

[14] M. Bragen, N. Collier, J. T. Murphy, J. Ozik, and E. Tatara, "http://repast.sourceforge.net/." [Online]. Available: http://repast.sourceforge.net/.

[15] KPMG, "Tanzania - Country profile," *TANZANIA - COUNTRY PROFILE BRIEF*,2012. [Online]. Available: https://www.kpmg.com/Africa/en/KPMG-in Africa/Documents/Tanzania.pdf.

[15] M. Bragen, N. Collier, J. T. Murphy, J. Ozik, and E. Tatara, The Repast Suite [Online, accessed on 31st June.2017]. Available: http://REPAST.sourceforge.net/.

[16] S. Kahrobaee, R. Rajabzadeh, L. Soh and S. Asgarpoor, "A Multiagent Modeling and Investigation of Smart Homes With Power Generation, Storage, and Trading Features", IEEE Transactions on Smart Grid, vol. 4, no. 2, pp. 659-668, 2013.

[17] S. Kahrobaee, R. Rajabzadeh, L. Soh and S. Asgarpoor, "Multiagent study of smart grid customers with neighborhood electricity trading", Electric Power Systems Research, vol. 111, pp. 123-132, 2014.