A Framework for Intelligent Control of SIRES for Rural Communities

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***Abstract*—A vast majority of people living in rural areas around the world lack access to fundamental needs. Smart Integrated Renewable Energy Systems (SIRES) can "energize" the rural area and not just "electrify" them. The essence of SIRES is matching resources to needs *a priori* to fulfill them in a smart and efficient way. SIRES comprises of several renewable technology devices, sensors and controllers. In order to satisfy the demands in an efficient manner, an intelligent control is necessary to actuate the system component controllers. For this, fuzzy logic based control is formulated in this paper. It is aided by forecasting one-hour ahead demand using neural network. A framework for fuzzy logic with associated membership functions and fuzzy rules is presented.**

I. Introduction

A rapidly growing world population coupled with increasing energy consumption has significantly increased the use of fossil fuels in the past decades. Burning fossil fuels is leading to high levels of CO_2 and climatic changes. Ever-increasing need for energy combined with global climatic concerns is opening up new opportunities for sustainable energy sources. In addition, significant cost reductions in the past few decades have made renewable energy sources competitive with fossil fuels. One of the most promising markets for renewable sources exist in supplying energy to remote rural areas, especially those who lack basic energy needs [1]. Table I gives a summary of percentage of people living in rural areas who are deprived of the basic energy needs. Energy is the key for overall development of rural areas and is required to improve the basic living environment [2].

TABLE I
Percentage of Energy Deprived Rural Areas [2]

Basic Needs	Population without access (in world)	Percentage living in rural areas
Safe Water	750 million	90%
Proper stove for cooking	2.5 billion	85%
Electricity	1.3 billion	85%

Various approaches have been proposed for the development of rural areas including the IEEE Smart Village as discussed in detail in [2]. A unique approach for rural development called Integrated Renewable Energy Systems (IRES), was introduced about five decades back [4]. The distinctive principle of IRES is that resources are priortized and matched to needs to fulfill them in an efficient and cost effective manner. Smart Integrated Renewable Energy System (SIRES) is smarter and improved version of IRES. In SIRES, smart sensors are strategically placed at locations where the amount of resources and status of system controllers have to be monitored. Intelligent controllers will be used to turn on/off renewable technologies. It is vital to control the controllers in an intelligent manner in order to fulfill the needs such as cooking,electricity, water for domestic and irrigation purpose in an efficient manner. In this paper, neural network is used forecast hourly ahead demand and fuzzy logic control is employed to actuate renewable technology devices to satisfy the forecasted demand. Components of SIRES and a schematic diagram with its components are illustrated in section II. In section III, detailed explanation for intelligent control for SIRES is presented. Finally, concluding remarks are succinctly presented in section IV.

II. Smart Integrated Renewable Energy Systems (SIRES)

The fundamental principle of SIRES is to use several renewable energy sources and match them to needs of remote rural in an efficient and economical manner. SIRES employs various energy resources, conversion technologies, and end-use technologies to provide a variety of energy and other needs. It primarily comprises of biogas digesters and stoves, wind-electric conversion systems, wind mechanical conversion systems, PV modules, PV-powered water pumps, micro hydro power plants, elevated water storage tanks, biogas powered generator, biogas powered water pump, batteries, fuel cells, converters and inverters. Fundamental needs of rural areas include potable and domestic water, water for irrigation, medium grade thermal energy for cooking, low-grade heating, and electricity for lighting, communication, cold storage and educational purposes. One possible schematic of SIRES utilizing numerous resources and needs at a particular site is shown in Figure 1 [2].

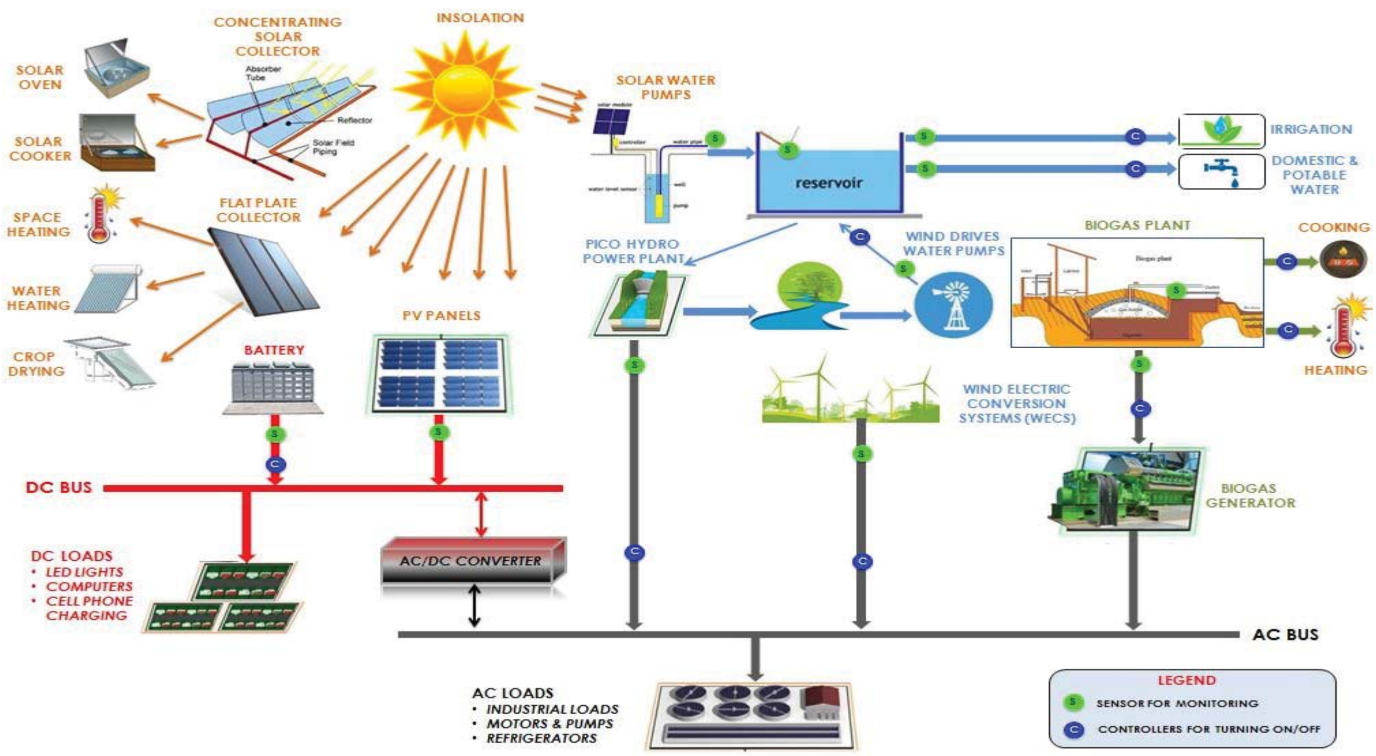

Fig. 1. Schematic diagram of SIRES [2]

A. *What is smart about this approach?*

Several aspects of SIRES make it smart. Firstly, SIRES maximizes the impact by energization as compared to electrification which is not efficient and cost-effective for demands such as cooking, water pumping etc. Although electricity can be used for cooking, it is more efficient and cost-effective to use biogas instead. Similarly, it is smart to use wind and solar based pumps to pump and store water in an overhead reservoir for distribution and for energy storage. Secondly, needs are prioritized based on necessities of daily life. For example, cooking would be on a higher priority when compared to electricity, and water for domestic purpose would be on a higher priority when compared to irrigation water. Resources are matched to needs a-priori. Third aspect of SIRES that makes it smart is genetic algorithm, which optimizes the operation of system components to minimize annualized cost of system and maximize reliability. Lastly, operation and resiliency are enhanced by using smart sensors and intelligent controllers. Data obtained from the sensors can be transmitted through a basic telemetry/cellular network for use in further research and improvement [2].

III. Intelligent control of SIRES

A comprehensive diagram for intelligent control of SIRES is illustrated in Figure 2.

A. *Neural network forecasting*

Forecasting the demands is one of the most significant aspect of control for SIRES. Similar day approach, regression models, neural networks, expert systems, fuzzy logic, statistical learning algorithms and so on are widely used for forecasting. Amongst these methods, neural networks have been universally accepted to be one of the most efficient methods for short term forecasting [5]. Neural Networks (NN) offer the ability to model the non-linearities that are known to be part of the demand pattern. Another advantage of NN is to automate the process of constructing forecasting model. Given the set of examples of demand and related variables, NNs can construct a model automatically [6].

1) Selecting the Architecture: Forecasting or prediction requires the use of dynamic neural networks since it is classified as time series analysis or dynamic modeling. For the purpose of dynamic modeling, Non-linear AutoRegressive model with eXogenous input (NARX) is suitable. This network has an advantage of being trained using static backpropagation algorithm because the tapped-delay-line at the input of the network can be replaced with an extended vector of delayed input values [7]. NARX neural network architecture is shown in Figure 3.

2) Data Collection: For the proper control of SIRES, it is required to predict the needs such as biogas for cooking, domestic water, electricity and irrigation water, which are output variables of NN. These needs depend on weather

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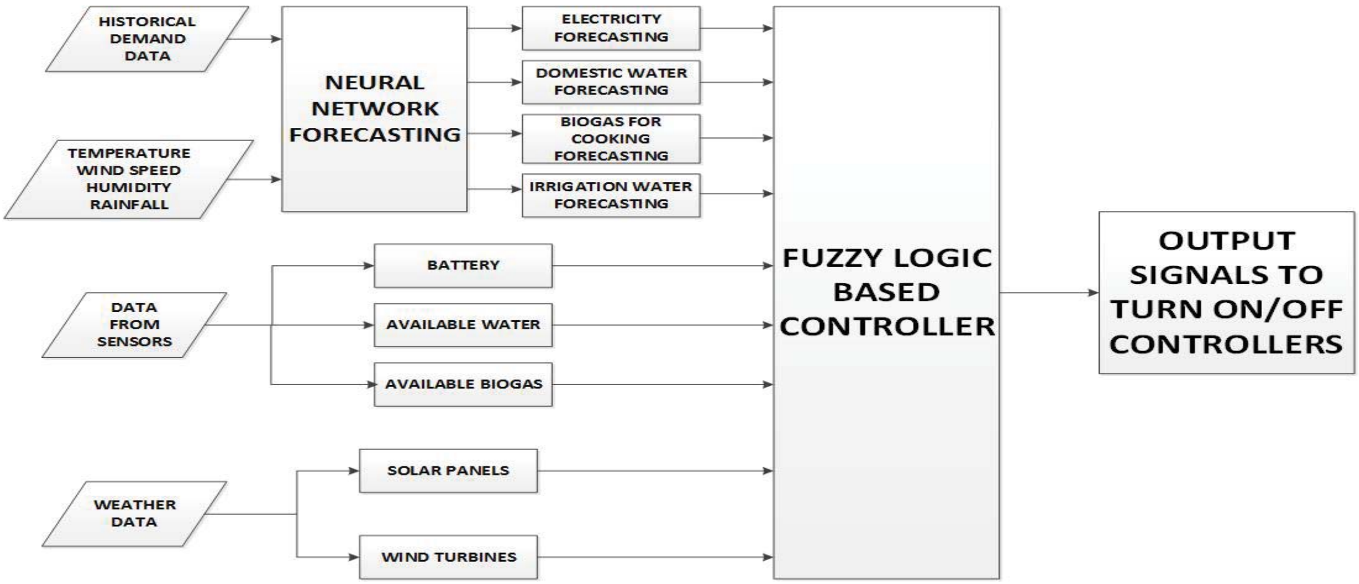

Fig. 2. Schematic diagram of intelligent control for SIRES

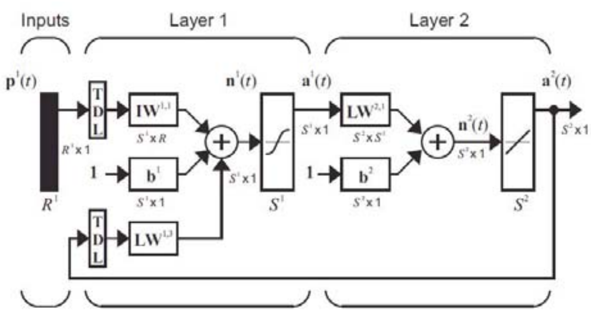

Fig. 3. NARX Neural Network [7]

conditions such as temperature, wind speed, humidity and rainfall. Hence weather conditions are the input variables to NN. One year of hourly data (8760 data points) for both input and output variables are used for training the NN. Hourly weather data for one year is obtained from the Climate and Data Services, Oklahoma Climatological Survey. A typical rural area with population of 700 in 120 households and 450 cattle is considered as an example for SIRES. Most of the people have agriculture as their basic occupation. 200 acres (80 hectares) is considered for agriculture. Every person requires about 0.34-0.42 m^3 of biogas every day for cooking purpose [8]. Therefore for 700 people, about 238-294 m^3 for biogas is needed every day for the rural area. Pattern of biogas consumption for cooking is decided empirically. Average level of water consumption per capita for domestic use in rural area is 71.3 liters [9]. To obtain the pattern of consumption of domestic water, water utility engineer at City of Stillwater was contacted. Hourly water consumption for one year is collected. Urban water usage is more compared to rural areas. Hence the water consumption is scaled by 2/3 to match the average consumption per capita in rural area as mentioned earlier. Electricity demand for 120 households varies from 300 kWh-360 kWh. For community purpose, it is assumed to vary from 45 kWh-55 kWh. Hence the total electricity consumption for the rural area will vary from 345-415 kWh. As mentioned earlier, 80 hectares need to be irrigated. Considering efficient irrigation and effective rainfall, it is estimated that 100-130 m^3/hour is required for irrigating the whole agriculture land [10].

3) Training Neural Network: Neural network toolbox in MATLAB is used to develop the NARX network. Levenberg-Marquadt (LM) algorithm is used to train the NARX network. Number of neurons in the hidden layer was set as 40 neurons and the delay is set as 4. Data collected is divided into training (70%), validation (15%) and test sets (15%). The network was trained for 1000 iterations until an acceptable Mean Square Error (MSE) is obtained.

B. Fuzzy Logic based Controller

Control of SIRES is a challenging problem since the mathematical model is difficult to build. In addition, SIRES consists of numerous renewable technology devices which needs to be triggered depending on the demands. In this paper, fuzzy logic (FL) based control is applied to turn on/off renewable technologies devices. FL has not only excellent expression ability of general knowledge but also powerful reasoning ability of expert system. If exact mathematical mode is difficult to build, FL can provide suitable tool for system controlling [11]. Further, FL can encompass such subjective decision-making process due to its ability to define human reasoning that can handle uncertainties regarding to the SIRES exogenous environment and the uncertainty of the forecasted parameters. Such approach can be easily extended to SIRES irrespective of the generation rating and the architecture of its components [12]. Fuzzy Logic Designer toolbox in MATLAB is used.

1) Fuzzification: Four demands namely cooking, domestic water, electricity and irrigation water are to be fulfilled by SIRES. The objective of SIRES is to fulfill these demands in a cost effective and efficient manner.

To fulfill cooking demand, biogas is the only resource that can be used. Biogas is produced every hour at the rate of 12-15 m^3/hour and hourly cooking demand varies from 0-35 m^3 depending on the hour of the day. If biogas produced is not sufficient to fulfill the demand at that hour, then biogas stored is used to fulfill the demand.

$$\Delta C_1(t) = C_P(t) - C_D(t) \quad (1)$$
$$\Delta C_2(t) = C_P(t) + C_S(t) - C_D(t) \quad (2)$$

where C_P (t), C_S (t) and C_D (t) is biogas produced, stored biogas and biogas demand for cooking at hour t respectively.

For domestic water demand, water pumped by solar energy and wind energy is considered the highest priority, followed by stored water in reservoir and biogas powered water pump. Domestic water demand varies from 0-8 m^3 per hour. To fulfill this demand, it is necessary to turn on/off the water pumps depending on the need.

$$\Delta DW_1(t) = DW_S(t) - DW_D(t) \quad (3)$$
$$\Delta DW_2(t) = DW_S(t) + DW_W(t) - DW_D(t) \quad (4)$$
$$\Delta DW_3(t) = DW_S(t) + DW_W(t) + DW_B(t) - DW_D(t) \quad (5)$$

where DW_S (t), DW_W (t) and DW_B (t) and is water pumped by solar energy, wind energy and biogas respectively at hour t. DW_D (t) is the domestic water demand at hour t.

For electricity demand, electricity produced by solar energy and wind energy is considered the highest priority, followed by stored water in reservoir and biogas powered generator. Hourly electricity energy demand varies from 0-3.3 kWh. To fulfill this demand, it is necessary to turn on/off the generators depending on the need.

$$\Delta E_1(t) = E_S(t) - E_D(t) \quad (6)$$
$$\Delta E_2(t) = E_S(t) + E_W(t) - E_D(t) \quad (7)$$
$$\Delta E_3(t) = E_S(t) + E_W(t) + E_H(t) - E_D(t) \quad (8)$$
$$\Delta E_4(t) = E_S(t) + E_W(t) + E_H(t) + E_B(t) - E_D(t) \quad (9)$$

where E_S (t), E_W (t), E_H (t) and E_B (t) and is electricity produced by solar energy, wind energy, hydroelectric and biogas respectively at hour t. E_D (t) is the electricity energy demand at hour t. For irrigation water demand, water pumped by solar energy and wind energy is considered the highest priority, followed by stored water in reservoir and biogas powered water pump. Irrigation water demand varies from 100-130 m^3 per hour. To fulfill this demand, it is necessary to turn on/off the water pumps depending on the need.

$$\Delta IW_1(t) = IW_S(t) - IW_D(t) \quad (10)$$
$$\Delta IW_2(t) = IW_S(t) + IW_W(t) - IW_D(t) \quad (11)$$
$$\Delta IW_3(t) = IW_S(t) + IW_W(t) + IW_B(t) - IW_D(t) \quad (12)$$

where IW_S (t), IW_W (t) and IW_B (t) and is water pumped by solar energy, wind energy and biogas respectively at hour t. IW_D (t) is the irrigation water demand at hour t.

Membership function plots for ΔC_1(t), ΔC_2(t), ΔDW_1(t), ΔDW_2(t), ΔDW_3(t), ΔE_1(t), ΔE_2(t), ΔE_3(t), ΔE_4(t), ΔIW_1(t), ΔIW_2(t) and ΔIW_3(t) are the same and is shown in Figure 4.

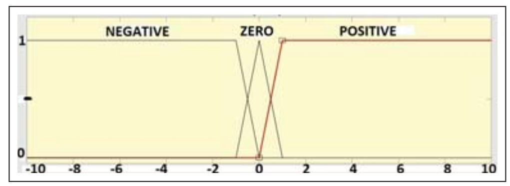

Fig. 4. Membership function plot

Membership function plots for biogas demand, available water in reservoir and charge available in battery are as shown in Figures 5, 6 and 7 respectively. If biogas demand is between 0 to 1 m^3, then membership assigned is Very Low.

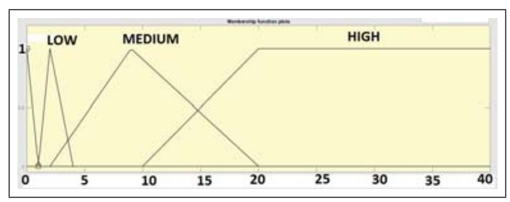

Fig. 5. Membership function plot for biogas demand

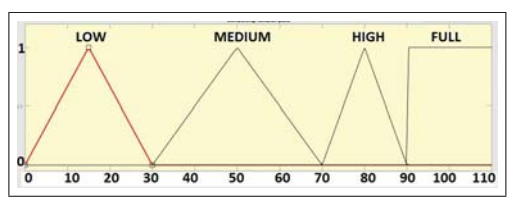

Fig. 6. Membership function for available water in reservoir

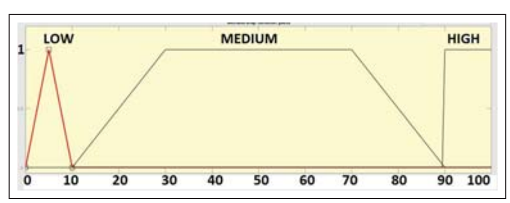

Fig. 7. Membership function plot for charge available in battery

Membership function plots for controllers of all system devices is shown in figure 8.

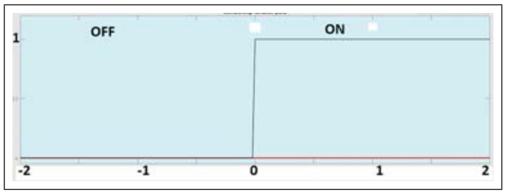

Fig. 8. Membership function plot for controllers

2) Inference Engine: Once the degrees of membership functions of each fuzzy set have been determined for a particular input, they are forwarded to the inference engine that defines which rules should be evaluated. Four demands need to be satisfied by SIRES. To fulfill each demand, several rules are developed. Examples for certain rules in each case are given here. It is important to note that all rules have not been mentioned.

Cooking demand

If ΔC_1 is Positive then BiogasforCooking is ON

If ΔC_1 is Negative and ΔC_2 is not Negative then BiogasforCooking is ON

If BiogasDemand is VeryLow then BiogasforCooking is OFF

Domestic Water demand

If ΔDW_1 is not Negative and Available-water-reservoir is not full then Solar is ON, Wind is OFF, Biogas is OFF

If ΔDW_1 is Negative and ΔDW_2 is Negative and Available-water-reservoir is high then Solar is ON, Wind is ON, Biogas is OFF

If ΔDW_1 is Negative and ΔDW_2 is Negative and Available-water-reservoir is low and ΔDW_3 is not Negative then Solar is ON, Wind is ON, Biogas is ON

Electricity demand

If ΔE_1 is Positive and Available-charge-battery is not full then Solar is ON, Wind is OFF, Battery is Charging, Hydropower is OFF, Biogas is OFF

If ΔE_1 is Negative and ΔE_2 is Zero then Solar is ON, Wind is ON,Hydropower is OFF, Biogas is OFF

If ΔE_1 is Negative and ΔE_2 is Negative and Available-charge-battery is low and ΔE_3 is Positive then Solar is ON, Wind is ON, Battery is Charging, Hydropower is ON, Biogas is OFF

If ΔE_1 is Negative and ΔE_2 is Negative and Available-charge-battery is medium and ΔE_3 is Negative and ΔE_4 is Positive then Solar is ON, Wind is ON, Battery is discharging, Hydropower is ON, Biogas is ON

Irrigation Water demand

If ΔIW_1 is Negative and ΔIW_2 is Negative and Available-water-reservoir is low and ΔIW_3 is Negative then Solar is ON, Wind is ON, Biogas is ON

If ΔIW_1 is not Negative and ΔIW_2 is not Negative and Available-water-reservoir is full and ΔIW_3 is not Negative then Solar is OFF, Wind is OFF, Biogas is OFF

3) Defuzzification: The last step in fuzzy logic control is defuzzification. If the output is positive, the corresponding renewable technology device is turned on. On the contrary, if the output is negative, the corresponding renewable technology device is turned off.

IV. Conclusion

SIRES is an effective and sustainable means to energize remote rural areas in a cost-effective and smart way. It is capable of utilizing several resources such as biogas, water, solar irradiation and wind simultaneously to supply basic needs such as cooking, domestic water, electricity and irrigation water. It employs a strategic *a-priori* resource-need matching and prioritization of resources and needs based on economic and end-use considerations. NARX neural network is used to forecast one-hour ahead demands. Forecasted demand is given as input to fuzzy logic control which makes the decision to switch on/off the corresponding renewable technology devices. In this paper, a framework of fuzzy logic control and neural network for SIRES control has been discussed. Implementation of SIRES will bring about socio-economic development in rural areas and improve the basic living environment.

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