Microgrid Operation for a Low Voltage Network with Renewable Energy Sources for Losses Minimisation and Voltage Control

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***Abstract*— This paper present brief description of a Microgrid development project currently in progress. Initially, then Malaysian renewable energy policy is briefly highlighted. The objective of having Microgrid is discussed. The main components of Microgrid and the technique on how the Microgrid central controller was developed is also explained. The result from simulation study of Microgrid system in the project is presented to demonstrate the workability of the concept. The modeling and simulation is performed in DIgSILENT and MATLAB/SIMPOWERSYSTEM software. The simulation shows quite promising results. The Microgrid controller managed to control the voltage and frequency in both grid connected and islanding mode as well as maintained them within mandatory operational limit of respective operation code in Malaysia. An active power loss is also significantly reduced.**

***Index Terms*-- Microgrid, renewable energy, distributed generation, coordinated voltage control.**

I. INTRODUCTION

In Malaysia, integration of renewable energy (RE) resources into electrical grid is increasing substantially due to encouraging government policy and very attractive incentive. The government RE targeted that by 2020 is 11 % of Malaysian electricity generation mix is as depicted in Fig. 1. This percentage is targeted to increase exponentially (17% in 2030 and 73% in 2050) to support the Malaysian sustainable economic growth in the future [1-2].

Large amount of the RE as distributed generation (DG) however is expected to create challenges to power system operation due to variability of these resources. Thus, in response to these challenges, a new paradigm in operating power system with the significant presence of RE is proposedtp adopt.. In this new paradigm, a part of distribution network comprises of RE generators is suggested to be operated as a Microgrid [3-4]. Microgrid can be considered as a part of technology under Smart Grid to realized active management of distribution network [5].

Microgrid architectures are being investigated in different research projects in EU, the USA, and Japan with some implemented demonstration project. Important components of a Microgrid include central controller and energy storage. Different control options and strategies are being investigated in each of the above projects [3-4]. The factor influencing these includes energy market scenarios and type of resources available in those regions. Another important factor is the local renewable energy policy and incentives provided by the local government.

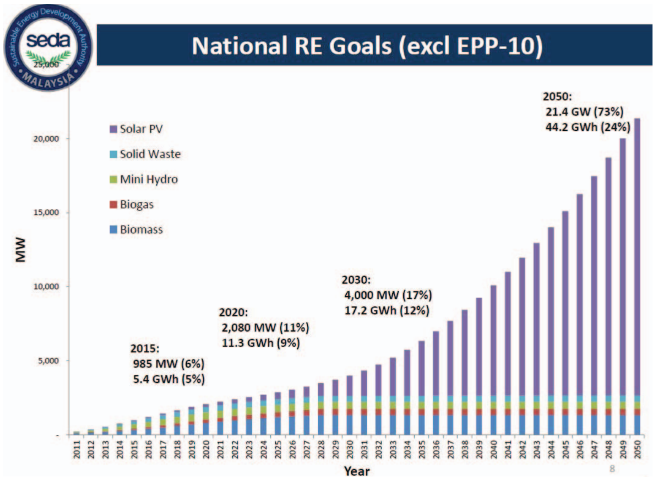

Figure 1. Malaysia National Renewable Energy Goals [1]

For example, Microgrid central controller in EU Microgrid architecture has several control functions that include optimizing generation and load scheduling based on daily forecasts and market prices; ensuring that the Microgrid satisfies the regulations of the distribution network operator; coordinating between different market agents in the Microgrid; and supervising islanding operation, load shedding and restoration, generator blackstart, resynchronization and system restoration [3-4].

This research works is part of collaboration works between TNB Research Malaysia and Power System Research Group of Universiti Kebangsaan Malaysia. TNB (Tenaga Nasional Berhad) is a main electric utility company in Malaysia and a leading utility company in South East Asia with almost MYR 87 billion in assets. TNB Research is a research arm of TNB. The funding is mostly provided by TNB Research.

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In the Consortium for Electric Reliability Technology Solution (CERTS) Microgrid, USA, for example, the Microgrid central controller is responsible for dispatching the output power and terminal voltage of DG [15]. The objective of operating Microgrid is however focusing on prototyping and demonstrating real-time reliability management tools, developing system security management tools, and conducting applied research on advanced measurement technologies and control[3-4].

In the Hachinohe demonstration project in Japan, the approach is quite different. In this project, the economic dispatch and weekly operation planning are the methods of Microgrid control where the main objectives are to minimize fuel cost and CO_2 emission. In addition, the controller has two additional control methods which are tie-line and local frequency control. The main objective of the later methods is to improve power quality [3-4].

In this research work, the main purpose of having Microgrid is to reduce the negative impact of PV output variation on the voltage and frequency. At the meantime Microgrid also is also expected to reduce active power losses in the network. The Microgrid controller should be able to manipulate the reactive power output from the renewable RE generators without reducing their active power dispatch capability. If this concept of control is proven successful, , it will be duplicated for a pilot implementation in one of distribution network in Malaysia.

II. MICROGRID POWER SYSTEM

Microgrid is a small power system with the ability to operate in parallel or independently with the main grid. Microgrid capacity extends from a few kilowatts to a few Megawatts. It is actually a cluster of small capacity generating units together with energy storage devices and controllable loads connected to a low voltage network and operated to supply the electrical enegy to local area for various purposes [6].

Microgrid concept is believed to be a part of evolution of power system that comprises distributed generation. The unique features of Microgrid are; it can be operated as a part of medium or low voltage network and it can also operate autonomously in an islanded mode, which enhances reliability of supply in case of faults in upstream network. It can be resynchronized back to the network after restoration of the upstream network. In Microgrid, distributed geneators (DG) will generate sufficient energy to supply most or all of the local load demand [3, 5-6].

The importance of having a pilot Microgrid test-bed is clear with the very ambitious government policy in promoting integration of RE in Malaysian generation mix. Most of RE are PV sources which is highly intermittent in nature. With substantial amount of RE generators, a lot of technical issues affecting the operation of the distribution network are expected to surface. These issues are voltage fluctuation, harmonics and increase in fault current level to name a few.

As Microgrid is a new concept, it requires a physical test-bed to prove its working concept before being implemented. Even though the control method proposed in [7-9] had been demonstrated to effectively control the voltage, the demonstration is only through digital simulation. There is no guarantee that the method works in the physical system. The need for a test-bed is recommended to test the method or any similar approach. The test-bed should contain various type of DG, communication infrastructure and programmable central controller in addition to typical equipments available in conventional electric distribution network.

Even though there are already a number of projects in progress all around the world, there are still a lot of challenges need to be overcome. RE resources are in different stages of maturity. It is quite a challenge in getting all of them operate together in a stable, concerted way to accomplish the goals of efficiency, security and reliability. Moreover each region has different energy policy and incentive on RE. These differences are evident from a number of projects which is already in progress influencing the objective of Microgrid central controller. Malaysia as a developing country located close to equatorial line has different energy policy and incentive on RE compared to advanced countries with temperate climate. The architecture and control objective of Microgrid in Malaysia will definitely be different to suit the local climate condition and scenario in the electricity supply industry.

III. MICROGRID COMPONENTS

The Microgrid under development is a part of low voltage network in one of TNB's owned premises in the central region of peninsular Malaysia. This Microgrid is comprise of photovoltaic generation sources, fuel cell generation sources, battery storage, adjustable load and two natural loads. The layout of this Microgrid is depicted in Fig. 2. Interfacing PV sources, FC and BES to 0.4 kV busbar, there are variable impedances to simulate the cable distance.

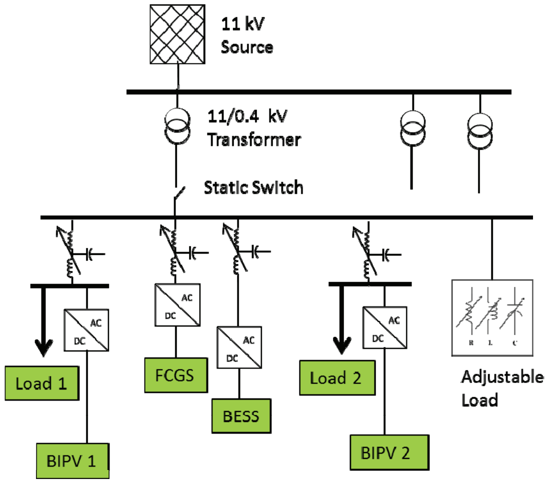

Figure 2. Proposed Microgrid architecture

IV. CONTROL OF MICROGRID

Microgrid controller is designed to operate autonomously by predicting and dispatching the power reference of the Microgrid active sources. Optimization process is used in finding the power references for these sources. The main objective is to keep the voltage inside Microgrid within operational limit at all times as in [10]. In the optimization however, the objective function is to minimize active power losses. The voltage magnitude is treated as a constraint.

TABLE I. MICROGRID COMPONENT

Component	Power Rating
BIPV 1	3.6 kVA
BIPV 2	4.0 kVA
FCGS	7.5 kVA
BESS	5 kVA
Adjustable load	5 kVA
Natural Load 1	5 kWp
Natural Load 2	5 kWp
Microgrid Controller	Not relevant
Static Switch	Not relevant

Mathematically, the optimization problem is written as,

$$\min P_{loss}(P_{FCGS}, P_{BESS}, Q_{PVGS}, Q_{FCGS}, Q_{BESS}) \tag{1}$$

where,

P_{FCGS} : active power of fuel cell generation system
P_{BESS} : active power of battery energy storage system
Q_{PVGS} : reactive power of PV generation system
Q_{FCGS}: reactive power of fuel cell generation system
Q_{BESS} : reactive power of battery energy storage system

The objective function is subjected to,

A. Cable loading limits

$$i_{line\_j} \le i_{line\_j}^{\max} \qquad \forall j \in N_C \tag{2}$$

B. Bus voltage limits

$$u_j^{\min} \le u_j \le u_j^{\max} \qquad \forall j \in N_B \tag{3}$$

C. RE active power limits

$$P_{RE\_j}^{\min} \le P_{RE\_j} \le P_{RE\_j}^{\max} \qquad \forall j \in N_{RE} \tag{4}$$

D. RE reactive power limits

$$Q_{RE\_j}^{\min} \le Q_{RE\_j} \le Q_{RE\_j}^{\max} \qquad \forall j \in N_{RE} \tag{5}$$

where N_B is the number of buses, N_C is the number of cables and N_{RE} is the number of RE units.

The optimization process is performed on the Microgrid network based on DIgSILENT power factory simulation model. The optimization process finds optimal power references for minimum active power losses while at the same time all the constraint are met. AC optimization interior point method is used as an optimization algorithm. The ptimization simulation is run for every one hour of natural load profile which are tabulated in Table II.

Building integrated PV (BIPV) output for the respective time is shown in Table III. The data is based on the hourly recorded output from the BIPVs installed in the premise. It can be seen that the maximum power generated by the BIPV is between 11:00 am and 4:00 pm. This is typical output of BIPV during clear sky day. During the cloudy day or rainy day, the output is less.

TABLE II. NATURAL LOAD PROFILE

Time	Hour	Load 1		Load 2	
		Active Power (kW)	*Reactive Power (kVar)*	*Active Power (kW)*	*Reactive Power (kVar)*
00:59	1	0.5527	0.2677	1.7573	0.8511
01:59	2	0.4900	0.2118	1.4196	0.6723
02:59	3	0.4880	0.2318	1.3257	0.6412
03:59	4	0.5029	0.2407	1.2701	0.6124
04:59	5	0.4858	0.2273	1.1577	0.5479
05:59	6	0.5024	0.2360	1.3558	0.6349
06:59	7	0.4918	0.2354	1.5446	0.7274
07:59	8	0.4696	0.2246	1.4728	0.6919
08:59	9	3.8537	0.2363	2.9568	0.8216
09:59	10	4.7795	0.2346	4.2805	0.8238
10:59	11	4.8456	0.2371	4.7294	0.7899
11:59	12	4.8495	0.2345	4.92[illegible]	0.6485
12:59	13	4.7016	0.2436	5.0000	0.7871
13:59	14	4.6573	0.2320	4.1959	0.6250
14:59	15	4.5172	0.2338	4.8131	0.6071
15:59	16	4.8540	0.2342	4.8518	0.7343
16:59	17	5.0000	0.2353	4.7822	0.7175
17:59	18	4.6525	0.2306	4.0937	0.7016
18:59	19	2.2780	0.2394	3.4434	0.7000
19:59	20	1.6379	0.2332	3.1250	0.6197
20:59	21	0.9992	0.2433	2.8912	0.6567
21:59	22	0.9665	0.2399	2.6122	0.8047
22:59	23	0.9264	0.2394	2.1702	0.8241
23:59	24	0.9408	0.2373	1.8858	0.8457

TABLE III. BIPV OUTPUT PROFILE

Time	Hour	BIPV 1 (kW)	BIPV 2 (kW)
00:59	1	0	0
01:59	2	0	0
02:59	3	0	0
03:59	4	0	0
04:59	5	0	0
05:59	6	0	0
06:59	7	0	0
07:59	8	0.4547	0.5052
08:59	9	1.0371	1.1523
09:59	10	2.1956	2.4396
10:59	11	3.2939	3.6599
11:59	12	3.2668	3.6298
12:59	13	3.3846	3.7607
13:59	14	3.0334	3.3705
14:59	15	3.5433	3.9370
15:59	16	3.2120	3.5689
16:59	17	2.2032	2.4480
17:59	18	0.9655	1.0728
18:59	19	0.1399	0.1554
19:59	20	0	0
20:59	21	0	0
21:59	22	0	0
22:59	23	0	0
23:59	24	0	0

The optimal power references are saved in the database. This data base is used to train artificial neural network for generalization. In this second stage, the Matlab software is used. The whole procedure is portrayed in Fig. 3.

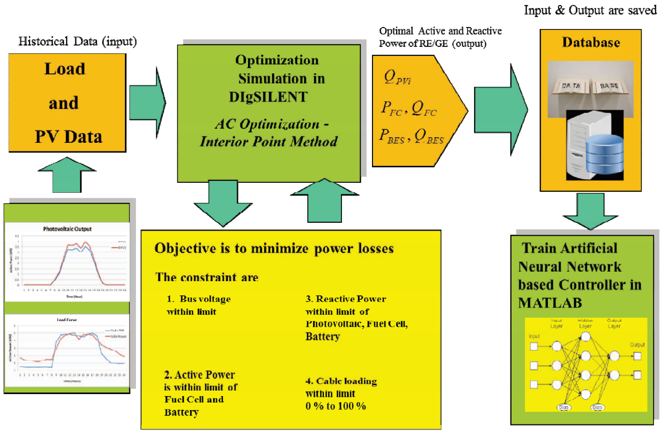

Figure 3. Microgrid controller development process

The Microgrid controller scheme that was developed is depicted in Fig. 4. The inputs are forecast of PV output from BIPV, instantaneous power from the upstream network and forecast of Microgrid natural load. The outputs are the BIPV reactive power reference and power reference for FCGS and BESS.

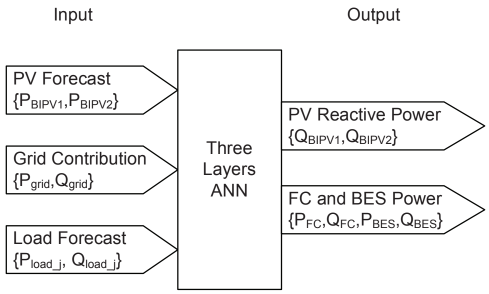

Figure 4. Microgrid controller input and output

V. MODELING AND SIMULATION OF MICROGRID OPERATION

All generation systems inside Microgrid are modelled as a three phase detail models. The whole Microgrid network with its components is depicted in Fig. 5. BIPV, FCGS? and Battery energy storage system (BESS) interface to the low voltage network via 3 phase power electronic converter utilizing IGBTs as switching devices. The switching of IGBT is controlled by signal generated by pulse width modulation method (PWM). The voltage references for PWM are calculated by inverter controller. The controller is implemented in *dq* coordinate which enable the independent control of active and reactive power. The inverter control method is explained in more detail in [6].

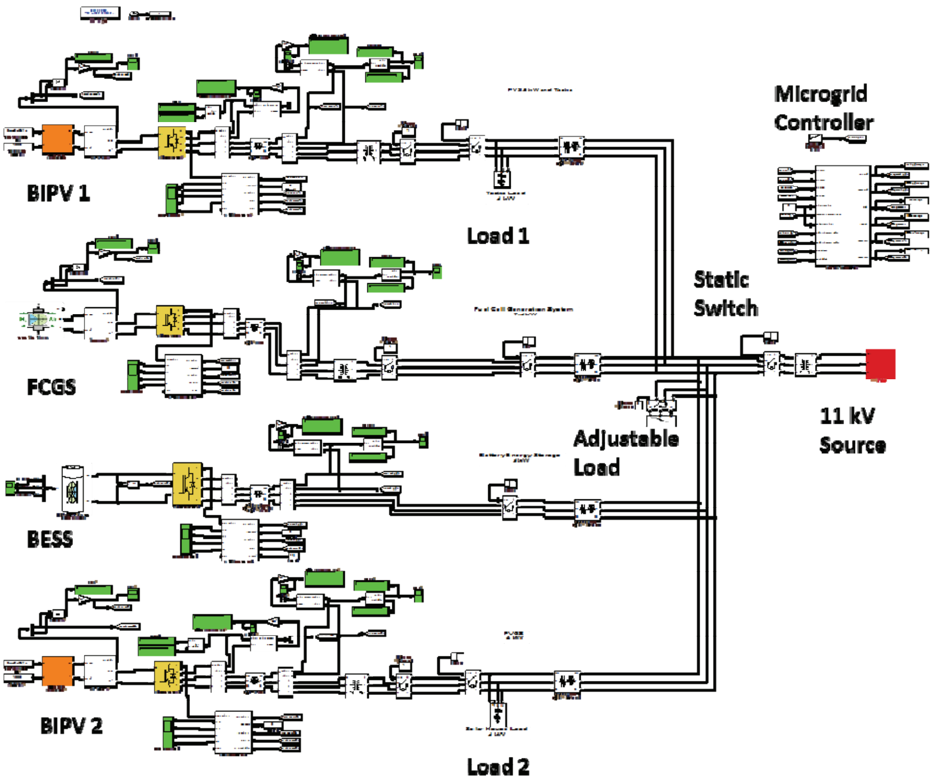

Figure 5. Snapshot of Microgrid model in SimPowerSystems

Fig. 6, Fig. 7 and Fig. 8 display the output voltage and current respectively from BIPV, FCGS and BESS. All the waveform is captured during full generation capacity at steady state operation. Voltage waveforms seem to be almost perfectly sinusoidal but the current waveform looks distorted. From detail analysis on the waveform, the total harmonic distortion for voltage and current are tabulated in Table IV.

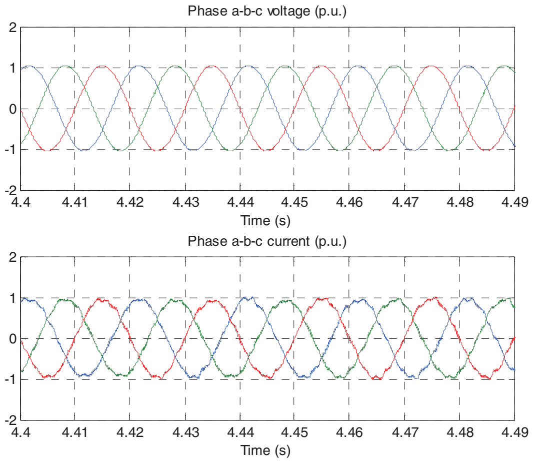

Figure 6. PVGS output voltage and current

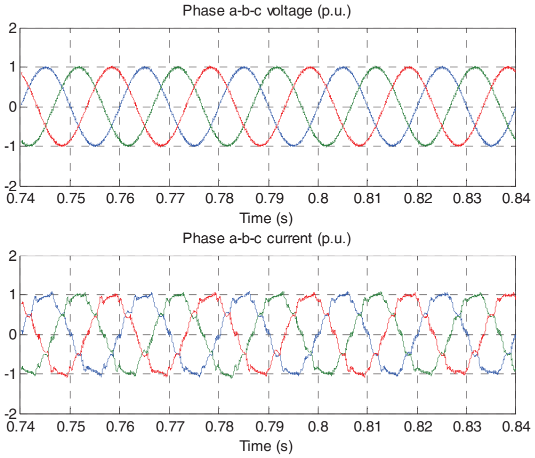

Figure 7. FCGS output voltage and current

As can be seen the Fig. 8 that current output from FCGS is more distorted as compared to the current output from BIPV and BESS as depicted in Fig. 7 and Fig. 9. With the Fourier transform analysis, the value of distortion for FCGS was calculated to be nearly 2% for THDv and close to 10% for THDi. This value are consider high for modern inverter that utilizing IGBT devices for switching. This is something interesting to be found. Even though the interfacing converter is utilizing exactly the same control algorithm, the distortion measured in current output is not similar.

This finding indicate that the individual converter is claimed to produce very low current total harmonic distortion typically less than 5% [4], when it is connected to the bigger electricity network, the current THD at the point of interconnection can be higher. This is due to the facts that a certain harmonic components resonate with the system impedance or the existing electrical network already contaminated with the harmonic. The addition, the converter contributes to higher harmonic contents.

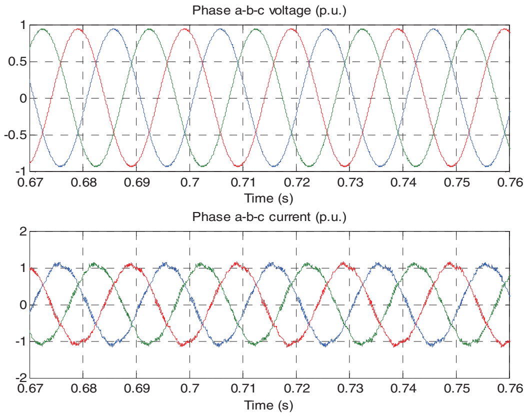

Figure 8. BESS output voltage and current

TABLE IV. TOTAL HARMONIC DISTORTION

Source	Voltage THD$_V$ (%)		Current THD$_I$ (%)	
BIPV	Phase a	0.35 %	Phase a	5.03 %
	Phase b	0.35 %	Phase b	4.95 %
	Phase c	0.34 %	Phase c	4.87 %
FCGS	Phase a	1.85 %	Phase a	9.31 %
	Phase b	1.86 %	Phase b	9.07 %
	Phase c	1.86 %	Phase c	9.45 %
BESS	Phase a	0.25 %	Phase a	4.75 %
	Phase b	0.26 %	Phase b	4.76 %
	Phase c	0.26 %	Phase c	4.62 %

To demonstrate the workability of the Microgrid model and the developed Microgrid controller, a simulation is run for 48 hours operation. This case is to demonstrate that the voltage and frequency can be maintained within allowable operational limit during both grid connected and islanding mode. The system is initially operated in parallel with the bigger network. At t = 18 hour, the static switch is triggered to open, the controller immediately transfer its operation to islanding mode. During islanding mode, the dispatch power from each generation inside Microgrid is change accordingly so that the voltage and frequency can be maintained within operation limit.

The dispatch power from each generation is depicted in Fig. 10. The voltage is shown in Fig. 11 and the frequency is portrayed in Fig. 12. For this case study, the allowable variation of frequency is ±1% of nominal frequency 50 Hz. For the voltage the tolerance is between +10% and -6% of nominal voltage of 400 V. This tolerance limits are the values gazetted in [5-6] and they are assumed to be the same for both grid connected and islanding mode for Microgrid. It is clearly seen that the frequency and voltage varies throughout the simulation but the variation is still within allowable tolerance.

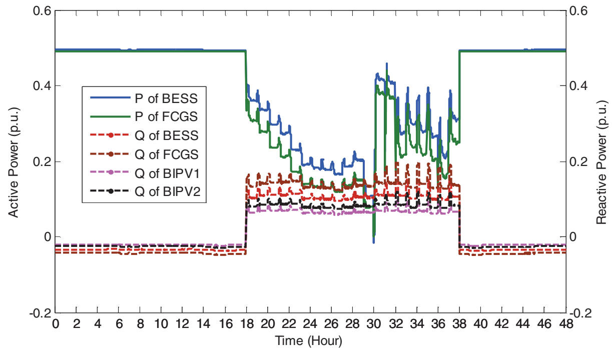

Figure 9. Active and reactive power references from Microgrid controller

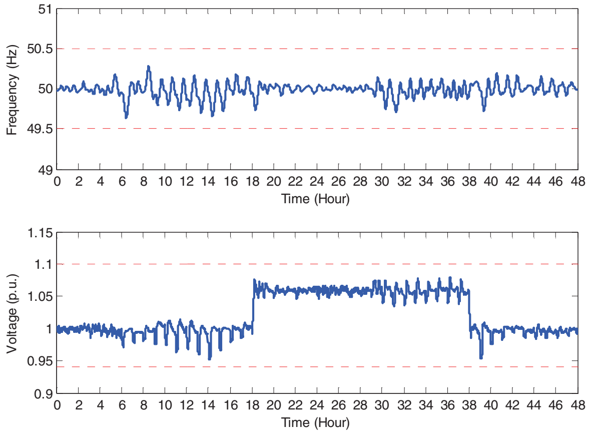

Figure 10. Frequency and voltage inside Microgrid

As the objective function is to minimise the active power losses, comparison is made to show the advantage of coordinately controlling the output of Microgrid components. It is clearly seen the losses is reduced up to 8 times.

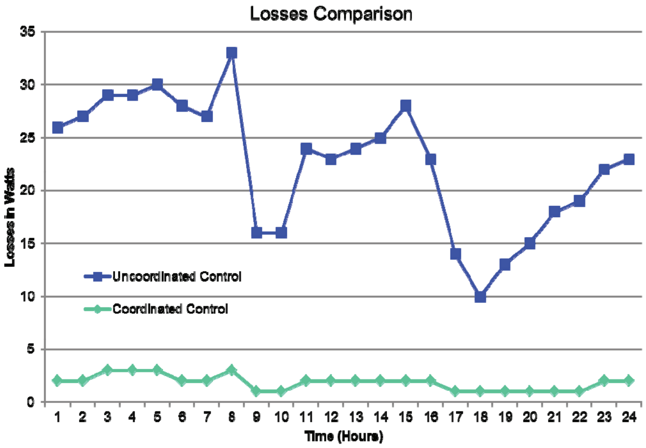

Figure 11. Active power losses comparison

VI. CONCLUSION

This paper has introduced briefly the renewable energy development in Malaysia and the government policy is mentioned. The reason for operating part of electricity network as Microgrid is also explained. Feature and components that constitute Microgrid is also described with the overview of Microgrid control feature for the Microgrid project developed in USA, Japan and Europe. A brief description of Microgrid development project at TNB Research is highlighted and the features as well as the component inside this Microgrid development are also described. The method of how the Microgrid central controller was developed is also explained. The result from simulation study of Microgrid system in the project is presented to demonstrate the workability of the concept. The simulation results show the promising results. The Microgrid controller managed to control the voltage and frequency in both grid connected and islanding mode as well as maintained them within mandatory operational limit of respective operation code in Malaysian.

ACKNOWLEDGMENT

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