Comparative Analysis of LLC Resonant and Quasi Resonant Converter for Photo Voltaic Emulator

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***Abstract*— The paper presents a comparative analysis of the two resonant based converter topologies. The converter topologies selected are LLC resonant converter and the Quasi resonant converter. The modeling, analysis and control of both the converter is done and presented here for the case of the photovoltaic (PV) emulator. A PV emulator is basically a DC-DC converter having same electrical characteristics that of solar PV panel. The emulator helps to achieve real characteristics of PV system in a better way in an environment where using actual PV systems can produce inconsistent results due to variation in weather conditions. The complete system is modelled in MATLAB® Simulink SimPowerSystem software package. The Simulation results obtained from the MATLAB® Simulink SimPowerSystem software package for both topologies under steady and dynamic conditions are analyzed and presented. An evaluation table is also presented at the end of the paper, presenting the effectiveness of each topology.**

Keywords—Buck Converter, LLC Resonant Converter, Quasi Resonant Buck Converter, Photo Voltaic Emulator, Simulink.

I. Introduction

The pollution caused by the burning/ consumption of fossil fuels in power stations, automotive vehicles etc. has led the society and researchers to think on the environmental lines. Energy obtained from naturally repetitive and persistent flows of energy occurring in the local environment is defined as renewable energy. Solar energy is a good example of renewable energy as it repeats day after day [1, 2].

Solar energy is being seen as one of the best renewable source of energy specialty in disconnected areas and it is becoming a popular solution to target energy problems in disconnected areas. Moreover, PV panels also finds application in independent systems for the production of electricity, such as solar home systems (SHS), street lighting, community facilities, etc. in isolated/ disconnected areas [3]. Power obtained from solar array depends upon solar insolation, climate etc. [4]. Hence, all the research and development activities required in the areas of solar energy requires a variable, stable and repeatable PV source for design and testing. Hence a PV generator emulator is required and its main function is to reproduce the I–V curve of a practical PV panel.

The development of the simulator was initiated/needed for the testing of PV applications such as three phase grid connected inverters or MPPT charge controllers as shown in Fig. 1. In Fig. 1, a DC-DC converter is used as solar PV emulator. The input is taken from a DC supply/source. The output of the PV emulator is given to the three phase grid connected inverter under test. Initially these tests were initially conducted on physical/real PV arrays, but many issues like changing weather etc. are associated with these types of tests [5].

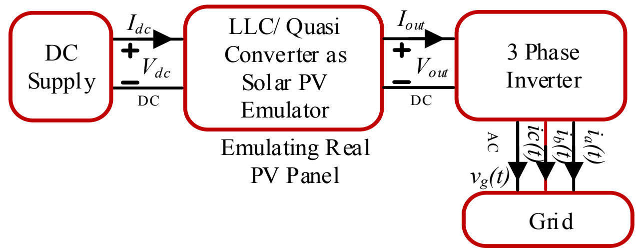

Fig. 1 PV emulator connection to a grid connected 3 phase inverter.

There are many types of solar PV panels available in the market, and it is uneconomical to buy all of these for testing to find the right product in terms of efficiency. A PV emulator is handy here as it can give the characteristics of all panels at different temperature and varying weather conditions, thus helping in the correct selection of real PV panel suitable to the particular requirement/ weather conditions. Simulation of a solar panel under various irradiances and temperatures is done using the mathematical model approach [6, 7]. In Photovoltaic systems, switched power DC-DC converters are widely used to transform power between one voltages to other and also mainly used in maximum power point tracker (MPPT) [8].

DC-DC converter has property of variable resistance which plays an important role to emulate solar I-V characteristics and its respective P-V curves of PV array [9-11]. A well designed solar PV emulator should have the following two features: 1) It should predict nearly same static I-V characteristics of real solar arrays and panel under various weather condition and load conditions. 2) It should be able to give satisfactory result under partial shading condition with more than one peak and step [12]. The DC/DC converter when designed properly can precisely describe the voltage-current and voltage-power characteristics of PV cell/array [13].

Many authors have contributed to the small-signal modeling of LCC resonant topology. A small-signal model for LCC

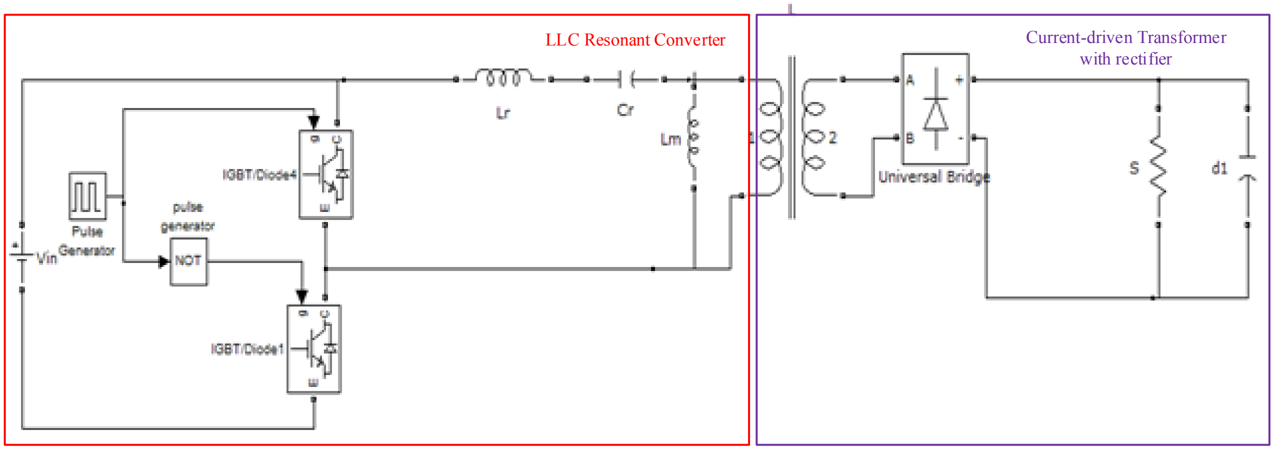

Fig. 2 Simulink block diagram of current mode control of LLC resonant converter

$$|M_V(\omega)| = \left|\frac{V_o}{V_{in}}\right| = \frac{1}{2n\{\sqrt{(1+A)^2[1-(\omega_L/\omega)^2]^2+(1/Q_L)^2((\omega/\omega_L)(A/1+A))-(\omega_L/\omega))^2\}}} \quad (1)$$

resonant converter with LC filter has been well explored for high-frequency applications. Dynamic modeling of LCC resonant topology with capacitive output filter for high-power applications has also been demonstrated by the authors in [14-15]. A new topology for Quasi-square-wave converters has been developed in 1988, and its detailed analysis and modeling is available in literature [16]. With all these research available, but still a comparative evaluation of the above topologies as a PV emulator is missing in the literature, and hence presented in this paper.

II. LLC Resonant Converter Based PV emulator

PV emulator can be implemented using LLC resonant converter (shown in Fig. 2). This types of resonant converter can be operated under zero-voltage switching (ZVS) for the high voltage side switch and zero-current switching (ZCS) of the rectifier diodes for the low voltage side when designed properly. The output impedance of the resonant converter can be regulated from zero to infinite without serial or shunt resistor with the frequency modulation control. Therefore, this type of inverter has significant higher than conventional PWM converter for this application. Voltage gain of the LLC resonant converter is given by equation (1).

Where,

$$A = \frac{L_r}{L_m} \quad , \quad \omega_L = 2\pi f_L = \frac{1}{\sqrt{(L_r+L_m)*C_r}} \quad \text{and} \quad Q_L = R_i \cdot \omega_L \cdot C_r$$

$$\omega_L = 2\pi f_L = \frac{1}{\sqrt{L_r*C_r}}$$

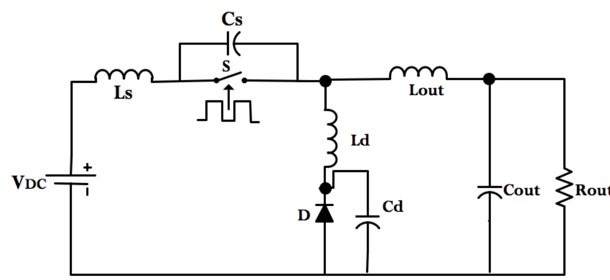

Fig. 3 Circuit Diagram of Quasi Resonant Buck Converter

III. Quasi Resonant Buck Converter Based PV emulator

Zero voltage switching can be obtained when capacitor is connected parallel across switch and zero current switching is obtained when an inductor is connected in series with the switch. Circuit diagram of Quasi resonant buck converter is shown in fig. 3. Regulation of the output voltage is achieved by changing the effective duty cycle, performed by varying the switching frequency of the switch. Thus, changing the effective on-time of the MOSFET in a ZVS design. The foundation of this conversion is simply the volt-second product equating of the input and output. It is somehow identical to that of Pulse width power conversion, and mostly not like those of its electrical dual of energy transfer system, the zero current switched converters.

Regulation of the output voltage is accomplished by adjusting the effective duty cycle, performed by varying the conversion frequency. This changes the effective on-time in a ZVS design. The foundation of this conversion is simply the volt-second product equating of the input and output. It is virtually identical to that of square wave power conversion, and vastly unlike the energy transfer system of its electrical dual, the zero current switched converters.

During the ZVS switch off-time, the L-C tank circuit resonates. Output voltage can be regulated by varying its switching frequency. the voltage across the switch start resonating from zero to its peak, and back down again to zero. At this point the switch can again be switched on, and lossless zero voltage switching is achieved. Because, the resonant tank discharges the output capacitance of the MOSFET switch (Coss), it do not contribute to power loss dissipated in the switch. Therefore, the MOSFET transition losses become zero regardless of circuit parameter i.e. operating frequency and input voltage. Therefore, it helps in improving the efficiency of the resonant converter. It also helps in decreasing heat losses associated with the MOSFET. This property of resonant converter makes zero voltage switching a suitable for high frequency, high voltage converter designs. Moreover, the gate drive requirements also reduced significantly in a ZVS design due to the lack of the gate to drain (Miller) charge, which is deleted when V& I equals zero.

$$V_{INmax} = V_{INmin} = V_{IN} = 30\ volt \quad (2)$$

$$V_{DSmax} = V_{INmax}(1 + I_{Omax}/I_{Omin}) \quad (3)$$

From equation 2 and 3, Choosing V_{DSmax} to be 6 times more than V_{IN} & I_{Omax}=4 amp

I_{Omin} will be .8 amp to achieve zero voltage switching.

A resonant tank period frequency of f_R=500 KHz will be used

Then $Z_R=V_{INmax}/I_{Omin}$ = 30/.8=37.5 ohm

L_R=Z_R/ω_R=37.5/2Π*50000 = 11.9 µH

$C_R=1/Z_R\ \omega_R$ = 8.45 nF

IV. Simulation Results and Discussion

Simulation is done in MATLAB® Simulink environment. The parameters used for LLC resonant and quasi resonant buck converters are listed in table 1 and table 2 respectively.The output voltage is 0-21 Volts, and output current is 0-4 amperes. The percentage ripple in output voltage and current is kept below 1%. Switching frequency is kept to about 100 kHz. Resonant impedance, inductance and capacitance has been calculated for quasi resonant converter and reported in the table as 75 ohm, 23.8µH and 4.225 nF respectively. Fig. 4 and 5 shows the frequency response of output voltage gain with different Q factor and diffent inductor ratios respeectively. Fig. 6 shows resonant current and magnetizing current for maximum power, whereas Fig. 7 shows diode current for the same case. It can be seen that diode is turning off with ZCS (zero current switching). Hence, there will not be any spike in the secondary diode current which increases overall efficiency. Fig. 8 shows output voltage at maximum power. Fig. 9 shows I-V characteristics of I-V curve and their corresponding frequency is shown in Fig. 10. It can be observed that points “E”, “F” and “G” are located in region 2 to obtain high efficiency in high output-power operations. It can be seen from above Fig. that in order to achieve full I-V characteristics frequency have to vary from 80 kHz to 175 kHz. But for half insolation as shown in Fig.9, in order to achieve open circuit voltage and short circuit frequency of LLC converter have to vary more. It is very difficult to build high variable frequency pulse generator and it will also increase gate driver circuit loss to a significant value. Therefore, efficiency of emulator will decrease.

Table 1. Simulation Parameters of LLC Resonant Converter

Simulation Set up Parameters	Rating
Input voltage	400 Volts
Output voltage	0-21 volts
Output current	0 -4 Amp
Maximum Power	66 Watts
Resonant frequency	100 kHz
Percentage ripple in current	less than 1%
Percentage ripple in voltage	less than 1%

Table 2. Simulation Parameters of Quasi Resonant Buck Converter

Simulation Set up Parameters	Rating
Output voltage	0-21 volts
Output current	0 -4 Amp
Switching frequency	80-120 kHz
Percentage ripple in current	less than 1%
Percentage ripple in voltage	less than 1%
Output Inductance of the converter (L)	1 mH
Output Capacitance of the converter (C)	1 mf
Resonant Impedance (Zr)	75 ohm
Resonant Inductance (Lr)	23.8µH
Resonant Capacitance (Cr)	4.225 nF
Output Min Current (I...)	0.4 A

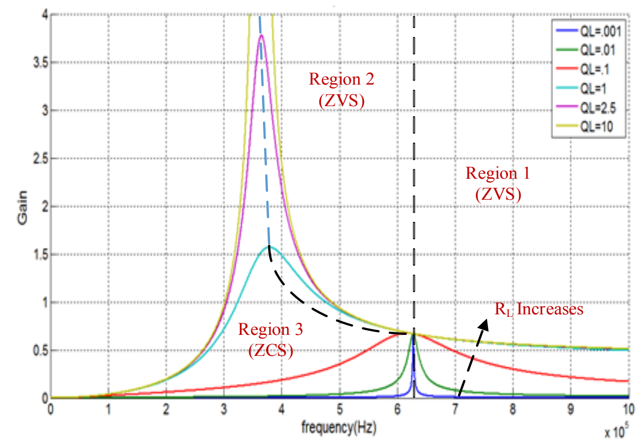

Fig. 4 Frequency response of output voltage gain of the LLC resonant converter

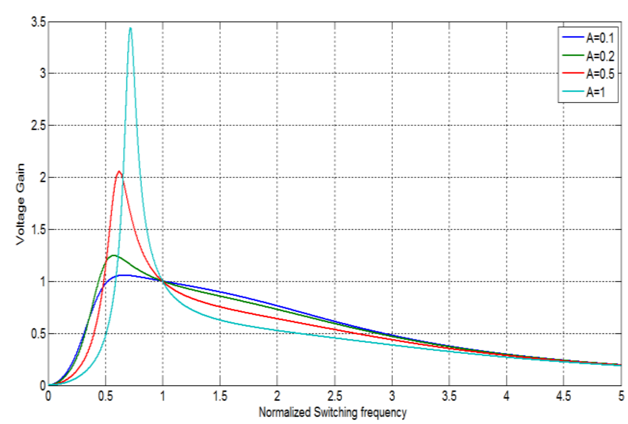

Fig. 5 Frequency response of output voltage gain with different inductor ratios

Fig. 11 shows resonant current at maximum power. Fig. 12 and 13 shows switch voltage v/s duty cycle of quasi buck

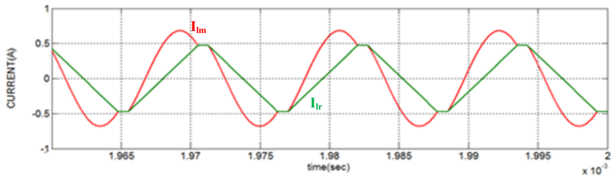

Fig. 6. Output Current at maximum power operating in region 2

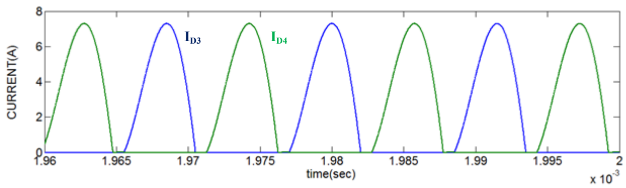

Fig. 7. Output Current at maximum power operating in region 2

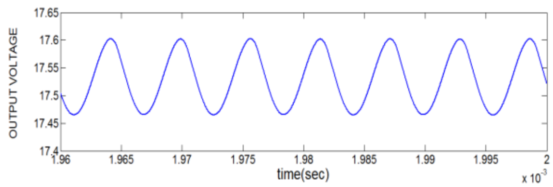

Fig. 8. Output voltage at maximum power

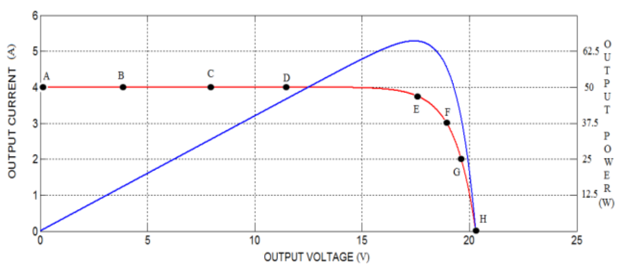

Fig. 9. The V–I curve of the LLC resonant converter

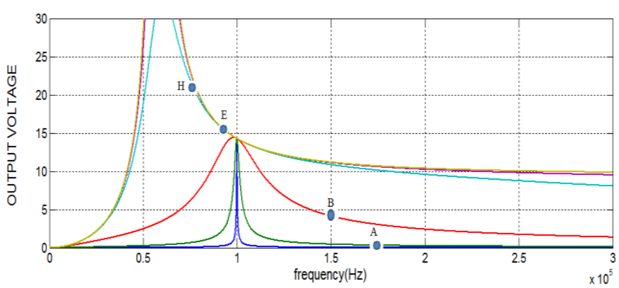

Fig. 10. Frequency response of output voltage gain

resonant converter. We can observe from Fig. 12 that ZVS of switch is achieved and maximum switch voltage is six times of input voltage as designed. If we want to achieve zero voltage for current less than 0.8 amps, we have to increase maximum switch voltage. Suppose we want to achieve zero voltage for current up to 0.4 amps. Then switch voltage will be 11 times of input voltage as shown in Fig. 13.

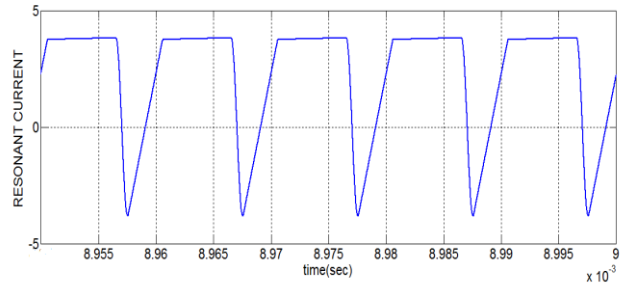

Fig. 11 Resonant Current at maximum power

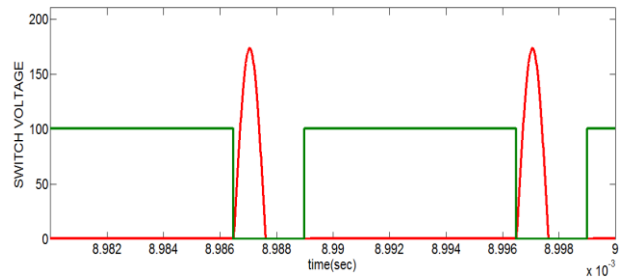

Figure 12. Switch voltage vs. duty cycle

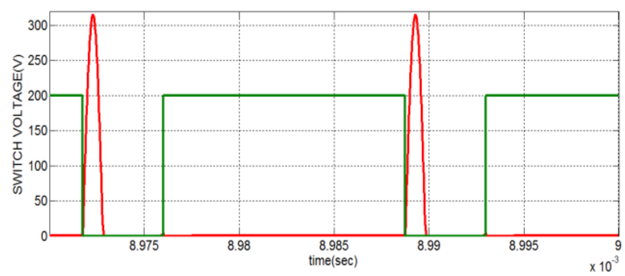

Fig. 13. Switch voltage vs. duty cycle

V. Conclusions

Two types of DC-DC converter has been studied, analyzed and simulated in the simulation environment for photo voltaic emulator. Resonant converter like LLC is very efficient for photo voltaic emulator if designed for particular solar insolation, but when this converter is used for variable solar insolation then the variation in switching frequency increase. It is impractical to build a gate driver circuit of wide frequency generator and also gate drive loss become significant while operating. Quasi buck also gives very good efficiency at maximum power point. But as discussed in section 4, in order to achieve full characteristics switch voltage have to increase. In order to achieve ZVS at open circuit condition, peak voltage will go to infinity. There is also problem at different solar insolation because for low value of solar insolation ZVS cannot be achieve on full I-V characteristics if short circuit current is less than I_{Omin}.

References

[1] F. Robert, M. Ghassemi, and A. Cota. “Solar energy: renewable energy and the environment”. CRC Press, 2009.

[2] M. Tariq, S. Bhardwaj and M. Rashid, “Effective battery charging system by solar energy using C programming and microcontroller”, American Journal of Electrical Power and Energy Systems, 2(2), 41-43. 2013.

[3] M. Tariq and K. Shamsi, “Application of RET to Develop educational infrastructure in Uttar Pradesh”. *International Journal of Recent Trend In engineering, ACEEE*, Vol. 4, pp 187-190, 2010.

[4] A. Tariq, M. Asim, and M. Tariq. "Simulink based modeling, simulation and Performance Evaluation of an MPPT for maximum power generation on resistive load." *2nd International Conference on Environmental Science and Technology IPCBEE*, Singapore, vol.6, Feb. 2011.

[5] D.C. Lu Dylan and Q. N. Nguyen, “A photovoltaic panel emulator using a buck-boost DC/DC converter and a low cost micro-controller”, *Solar Energy*, *Elsevier,* Volume 86, Issue 5, pp 1477-1484, May 2012.

[6] S. Yuliang, "A Photo-voltaic array simulator", *Acta Energiae Solaris Sinica*, vol.18, pp.448-451, 1997.

[7] L. Hongliang, H. Mingzhi and Y. Xiaojie, "Investigation of photovoltaic array simulators based on different kinds of PWM rectifiers," *Communications, Circuits and Systems, ICCCAS. International Conference on* , pp.737-741, 23-25 July 2009

[8] Duran, E.; Galán, J.; Sidrach-de-Cardona, M.; Andujar, J.M., "A New Application of the Buck-Boost-Derived Converters to Obtain the I-V Curve of Photovoltaic Modules," Power Electronics Specialists Conference, 2007. PESC 2007. IEEE, vol., no., pp.413-417, 17-21 June 2007.

[9] M. Tariq and S. Yuvarajan. Modeling and Analysis of Self Excited Induction Generator with Electronic load controller supplying static loads. Canadian Journal on Electrical and Electronics Engineering, 4(1), pp.9-13. 2013.

[10] M. T. Iqbal, M. Tariq, and M.S.U. Khan, M.S.U, “Fuzzy logic control of buck converter for photo voltaic emulator”. In 2016 4th International Conference on the Development in the in Renewable Energy Technology (ICDRET) (pp. 1-6). IEEE, 2016. , January.

[11] M. Tariq and M. T. Iqbal. Power quality improvement by using multi-pulse AC-DC converters for DC drives: Modeling, simulation and its digital implementation. Journal of Electrical Systems and Information Technology, 1(3), pp.255-265, 2014.

[12] K. Ahmed, T. LaBella and J. S. Lai. "High efficiency photovoltaic source simulator with fast response time for solar power conditioning systems evaluation." *Power Electronics, IEEE Transactions on* 29.(3) pp 1285-1297, 2014.

[13] Cirrincione, M.; Di Piazza, M.C.; Marsala, G.; Pucci, M.; Vitale, G., "Real time simulation of renewable sources by model-based control of DC/DC converters," *Industrial Electronics, 2008. ISIE 2008. IEEE International Symposium on*, pp.1548,1555, June 30 2008-July 2 2008.

[14] E. X. Yang, F. C. Lee, and M. M. Jovanovic, “Small-signal modeling of LCC resonant converter,” *in Proc. IEEE Power Electron. Spec. Conf*., Jun.1992, pp. 941–948.

[15] J. F. Lazar and R. Martinelli, “Steady-state analysis of the LLC series resonant converter,” *in Proc. IEEE Appl. Power Electron.Conf. Expo.Mar*. 2001, vol. 2, pp. 728–735.

[16] V. Vorperian, "Quasi-square-wave converters: topologies and analysis," *Power Electronics, IEEE Transactions on* , vol.3, no.2, pp.183,191, Apr 1988.

Electric Energy Access in Bangladesh

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Abstract— This paper represents the overall electrical energy profile and access in Bangladesh. In the recent past, Bangladesh has been experiencing the shortage of electricity, and about 42 % of the population no access to the electricity. The electricity consumption has rapidly increased over last decade. The demand and consumption will intensify in the remote future as overall development and future growth. To set "vision 2021" of Bangladesh; the government of Bangladesh has devoted to ensuring access to affordable and reliable electricity for all by 2021. In the modern time, energy is the vital ingredient for socio-economic growth in the developing country i.e., alleviating poverty. Along with electricity access in Bangladesh strived to become the middle-income country by 2021. Bangladesh has experienced that energy consumption inclines to increase rapidly when per capita income reaches between US$ 1,000 and US$ 10,000, and a country's growth momentum through reliable energy supply and consistent energy supply ensured by the sustainable energy. As increasing population in Bangladesh, the electric energy generation is an important dispute through the sustainable way.

Index Terms— **Energy Profile, Energy efficiency, Electric Power sector, Electricity reformation, Renewable energy access, Solar home system**

I. Introduction

According to report 2012, Bangladesh is the 134th ranked out of 144 countries on the quality of electricity supply, which suggests the most problematic obstacles to the further socioeconomic progress. The IEA estimates approximately 1.5 billion people have no access to electricity in 2008 [1], which estimates more than 20 % of total population. According to UNDP report more than 96.2 million of people which is more than half the total population in Bangladesh still remains without access to electricity city [2], furthermore, the irregular electric power supply causes load shedding. Electric energy access is the far-way dream for many families in the rural area in developing countries, about 80 % of the population are living in the rural and remote areas in Bangladesh where only 25 % of electricity available for people. Overcoming the curse of poverty, sustainable economic growth by access energy is an essential prerequisite and major criterion. Electricity access with a modern form of energy resources is promoting social and economic growth. It is also an indispensable contribution to achieving Millennium Development Goal (MDG) and vision 2021. In the modern era, there is no country attained sustained economic growth without improving access to clean and modern energy; the modern form of energy delineates with an integration of locally available renewable energy sources. Rural electrification ensuring with improved electricity is fundamental for socio-economic development. Electrical energy access influences to the life standards, which affecting agricultural productivity, education, health. The Government of Bangladesh has set a noble vision to access electricity for all inhabitants by 2021, to comply the vision integrating solar PV and biomass sources which are richly endowed in Bangladesh. In Bangladesh, it is common about 4 - 6 h of power outage per day in rural areas, but summer season the number of hours rises to 6 - 8 h, mostly during 18:00 - 22:00 h irregular power outage causes load shedding. The demand for electricity increases with increasing with Population but the generation of electricity is not increasing to meet the demand. At present, almost 52 % of total people in Bangladesh are connected to the grid [3], the power supply from the grid is inadequate to meet both peak and basic demand in Bangladesh. Almost 75 % of people in rural areas are not connected to the main grid, and only 15 - 20 % of electric demand comply by the BREB (Bangladesh rural electrification board) supplied electricity [4]. Due to life standards and social standards enhances, the consumption rate increased at 4.53 %, but the generation of electricity increased only at a rate of 5.37 % that increased

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the rate of 6.72 % load shedding per year [5], graphically present in figure 2-3. According to LEAP (long range energy alternative planning) project [6], rural households loads comprises with lighting, mobile charger, ceiling fan, TV, and refrigerators. In rural areas lighting are the main loads in the rural households. In 2010 rural households, consumes 300kWh per year for lighting solely satisfied by electricity supplies. The demand for lighting growing at constant 1.67 % per year to 350 kWh by 2020 [7]. A tropical country like Bangladesh, where summer seasons comprises almost 9 months requires cooling by the ceiling fan, consumes 250 kWh per year and assume the consumption rate increase up to 1.9 % to 345 kWh in 2030. Likewise, refrigeration consumption demand rate increase 0.93 %, the demand increases from 476 kWh to 565 kWh in 2030. The percentage of energy consumption has experienced promptly increasing about 2.69 % from 2012 to 2013, but still remains lowest per capita consumption. The studies of EIA, the consumption has increased dramatically over 52 % within the past decade [8]. If your paper is intended for a conference, please contact your conference editor concerning acceptable word processor formats for your particular conference.

II. General Country profile

Bangladesh is moving towards achieving the tag of Developing country with an annual GDP almost 6 % over the last past decade [9]. Recently population thriving dramatically nearly 158 million and annual growth rate of 1.39 % over the past decade [10]. The majority of them are living in the rural areas, and only 32 % of households have access to electricity, but the availability of electricity about 22 % [11]. Bangladesh is one of the largest in population at 9th position in the world with 158 million people at the end of 2014, where total 52 % people have partially electricity access, while only 10-15 % of rural have the access to electricity demand mainly meets the light, ceiling fan, refrigeration, irrigation, productive uses loads. In Bangladesh, the electricity demand of all sectors including agriculture, commercial service, industry, and domestic services. The domestic households and industry sectors are consuming of electrical power about 43 % and 44 % respectively in total of about 87 % [12]. The GDP growth rates significantly depend on the production of a country, as Bangladesh is an agricultural and small size industrial production based country, and production always depends on electricity, the GDP growth and electricity generation growth present in figure 1. It is estimated that 1 % increase in per capita energy consumption causes an increase in per capita GDP by 0.23 %.

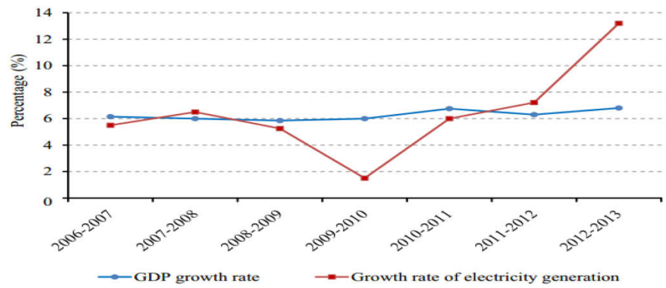


Figure 1: GDP Growth Rate with Electricity Access

A. *Demand of Electricity vs Climate of Bangladesh*

Bangladesh is located between 20° to 26° North and 88° to 92° east. It is bordered on the west, north and east by India, on the south-east by Myanmar, and on the south by the Bay of Bengal. The geographical location of Bangladesh offers higher solar irradiation [13]. Bangladesh enjoys generally a sub-tropical monsoon climate while there are six seasons in a year, with three being more prominent, namely winter, summer and monsoon season. Winter begins in November and ends in February. In winter, there is not much fluctuation in temperature, which ranges from minimum of 7° - 13 °C to a maximum of 24 °C – 31 °C. The maximum temperature recorded in the summer months is 37 °C although in some places this occasionally rises up to 41°C (105°F or more) [13]. As the temperature increases the demand for electricity has increased due to refrigeration, cooling, whereas the base load demand is higher than the electricity generation. Bangladesh has three main seasons: the monsoon or wet season from late May to early October; the cold season from mid-November to the end of January; and the hot season from March to mid-September [15]; the imbalance between demand and supply due to high electricity demand for ceiling fan, refrigeration during March to August in each year.

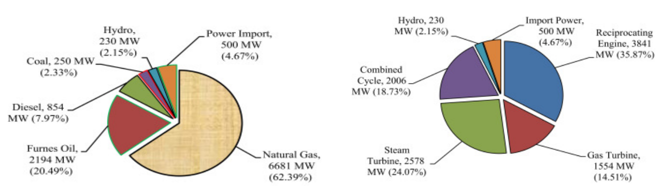
B. *Electric Energy Status and Demand Profile*

Electric energy is one of the affable terms of energy which is the fundamental contingent for socio-economic development, which alleviate poverty. But, Bangladesh has the major problem of the energy crisis that persisting poverty, conventional fossil fuel causes environmental degradation. Merely, 49 % of the population have the access electricity that met by 4500 MW while peak demand 6000 MW causes the power outage. Currently, 53 % electricity produced by public sectors and rest produced by several private sectors with various form of generation [16]. The existing available power generation 8,500 MW by October 2014 and vision set to 39,000 MW by 2030 [17]. The (table-1), represents power generation from different organization and Bangladesh Power Development Board (BPDB) transmits and distributes across the country. Natural gas and coal expected the main source of power generation in Bangladesh, GOB also attentive on liquid fuel based power generation. The conventional fuel consumption to generate electrical power and traditional power plant influenced to increase CO_2 emission, power generation sector alone contributes 40 % CO_2 emission [18]. The primary energy considered to consumption estimated 62% of biomass, 25 % of natural gas, 12 % imported oil, and coal and hydropower contribute 1 %.

Table 1: Daily Power Generation

Company	Demand (MW)	Day peak (MW)	Evening peak (MW)
Power Development Board	4332.00	1767.00	2702.00
Electricity generation company Bangladesh Ltd	622.00	0.00	0.00
Ashuganj Power Station Co. Ltd	1617.00	723.00	896.00
Independent Power Producer (private)	325.00	248.00	283.00
Small size producers	1987.00	1269.00	1440.00
Rental Power Producers	825.00	1101.00	1189.00
Total generation	10390.0	5515.0	6987

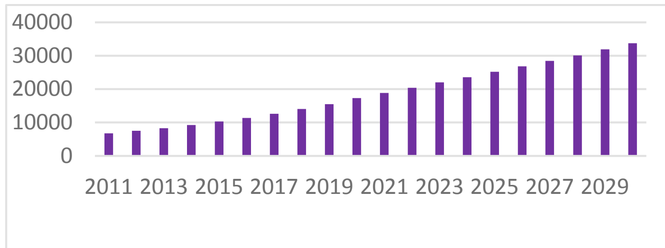
In Bangladesh, power sectors that highly dependent on conventional fossil fuel including gas and coal. The total capacity of electricity generation about 8,709 MW, and 62.9 % of electricity generation by natural gas present in figure 2. Besides natural gas, 10 % high-speed diesel, 5 % of coal, and 3 % of heavy fuel oil used to produces electricity figure 2(a). Besides natural gas, 10 % high speed diesel, 5 % of coal, and 3 % of heavy fuel oil used to produces electricity [20], and only 3.3 % of electricity contributes by renewable sources [21].



(a) (b)

Figure 2: Installed electricity capacity (a) fuel type and (b) plant type [19]

According to (BPDB) report expresses, 55 % of people have access electricity, and per capita 321 kWh electricity generation [22], which comparatively lower than other developing countries. Access to power in Bangladesh is limited to about 45 % – 50 % of the population and those who have access faces severe power shortages. Load shedding in Dhaka in 2011 and during the summer of 2012 was about 5 hours per day. Power shortages have constrained the potential economic growth in Bangladesh and cost of which have been estimated to be about 0.5 % of GDP. According to "Vision 2021"; the government's vision for the power sector is to ensure universal access to grid electricity by the year 2020, with an interim target to reach an access level of 68 % by year the 2015. According to government estimates, about 20,000 megawatts (MW) of new generation capacity need to be added to the system by 2020, together with matching transmission and distribution improvements to reach the universal access [23].



Yearly Electricity Demand (Anticipated)

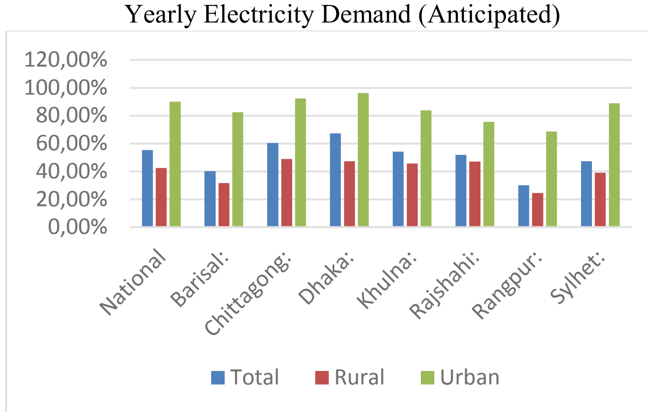


Figure 3: Electrification Rate in Different Regions

The total installed capacity was 5262 MW in FY 2007–08, which has increased to 8525 MW in FY 2012–13 with an annual increase of 10.34 %. However, the maximum generation was 4130 MW in FY 2007–08, which has increased to 6350 MW in FY 2012–13 with an annual increase of 8.96 %. The annual rise in maximum generation (8.96 %) is lower than that of the installed capacity (10.34 %) between the FY 2007–08 and 2012–13. This is mainly due to the less generation capacity of older power plants and shortage of gas supply.

Table 2: Different fuel Consumption

Gas	Diesel	Hydro	Coal	Furnace
4822 MW	186 MW	230 MW	250 MW	335 MW
82.81%	3.19%	3.95%	4.29%	5.75%

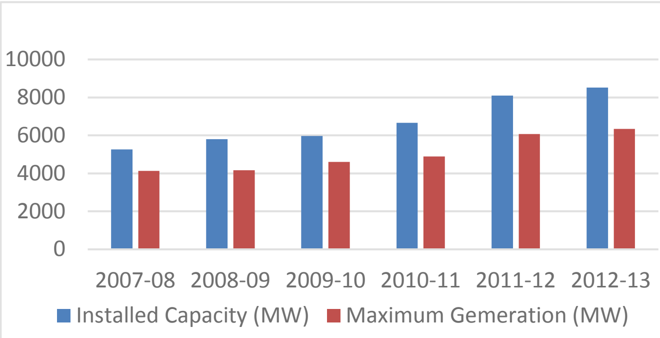


Figure 4: Installed Capacity and Generation 2007-2013

Though attribution is difficult, this technical assistance may have played a role in supporting a 'balanced development' of the power sector, which during the project period (2004-2013) saw an increase in electricity access from 35 percent to about 62 %; an increase in generation capacity from 3,622 MW in 2004 to 9,500 MW; a reduction of systems losses from about 20.0 percent to 1.3 percent; and a drop in accounts receivable from 6.45 months to 2.21 months. About 40 % of electricity generated by private enterprises by April, 2010 while the number has been increased to 44 % by April 2011. Currently, rental, quick rental and some others peaking plants were under taken on a first track based power generation to manage present power crisis. According to the Power System Master Plan (PSMP), the peak demand anticipated 10,283 MW in 2015, whereas total power generated about 12071 MW. The anticipated peak demand 25199 MW anticipated in 2020 and 33708 MW in 2030 show in figure 5.

C. Infrastructure of Bangladesh Power development

First Bangladesh Power Development Board (BPDB), is the sole authority to delivered electricity to the national grid through a common transmission line, to meet the national demand BPDB produces and purchases electricity from independent power producers (IPPs). The five authorities contributes together to produces electricity in Bangladesh:
(i) Bangladesh Power Development Board (BPDB)
(ii) Ashuganj Power Station Company Ltd. (APSCL)
(iii) Electricity Generation Company of Bangladesh (EGCB)
(iv) North West Power Generation Company
(v) Independent Power Producers (IPPs)

Table 3: Authorities of Power Generation and Capacities and Market Share

Name of Authorities	Capacity (MW)	Market Share (%)
Bangladesh Power Development Board (BPDB)	4442	42.75
Ashuganj Power Station Company Ltd (APSCL)	682	6.56
Electricity Generation Company of Bangladesh	622	5.98
North West Power Generation Company Ltd	375	3.06
Independent Power Producers (IPPs)	4269	41.08
Total	10390	100

Considering country size and population, Bangladesh electricity infrastructure are quite smaller than other countries which is insufficient and poorly managed by several authorities including BPDB, BPDC, DESCO and REB. Amongst all these authorities, REB is one of the most success government company since 1977 in Bangladesh, 40.10 % electricity purchased to electrifying rural areas.

Table 4: Share of electricity distribution by Authorities

Authority	BPDB	DPDC	DESCO	WZPDC	REB
Share (%)	24.64	18.59	10.51	6.17	40.10

Bangladesh power system including transmission system comprises along with 16 substations capacity of 230/132 kV besides that 103 substations dimensions of 132/33 kV substations, which total capacity of power contains 7525 MVA and 11892 MVA respectively. The distribution network comprises 33 kV, 11 kV, and 400 V [27].

III. RURAL ELECTRIFICATION

South Asia accounts for 37 % of the world's population without access to electricity [28]. Such a situation continues to exist despite several initiatives and policies to support rural electrification efforts by the respective country governments including the use of renewable energy technologies including PV, wind, and biomass. The pace of rural electrification over much of the developing world is excruciatingly slow. In many countries in South Asian and Sub-Saharan African, it is even lower than rural electrification growth in Bangladesh. Bringing the socio-economic development into the development countries like Bangladesh, the essential elements considers rural electrification [29], development of underprivileged rural people [30] [31]. Demand for electricity with an improvement of living standard, agricultural production, community development in Bangladesh. Energy access through rural electrification level still not sufficient enough, but the impressive SHS growth and off-grid PV system in

Bangladesh. Development and implemented by IDCOL (Infrastructure Development Company Limited).

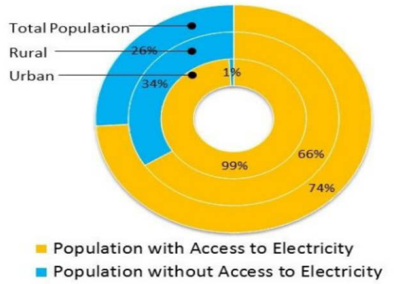


Figure 3: Electric Energy Access

Electrification rate in rural areas still poor as only 38 % of households is electrified [11], IDCOL (Bangladesh Government owned agency) with other 30 partners Organization (POs) working together for improving the access of electricity around rural areas. Despite of continuous efforts from the international community and governments, the pace of rural electrification still very slow [34]. The Bangladesh Rural Electrification Program (BREP) clearly expresses which benefit greatly from the involvement of local communities improve electricity access in rural areas. According to the vision 2021; GOB aims at 100 % access to electricity to entire rural areas by 2020, Connecting over 0.7 million consumers and only 3 % of electricity supplied by the REB, the dedicated government organization, rest of can be supplied by the including private company and partner organization (POs). The process of rural electrification in developing countries, which depends on various factors;

(1) The result of pre-phase economic and social impact
(2) Development of PBS (local partner)
(3) Technically and financially power system
(4)Available funding from international; community

There is the main process of electrical access in rural areas centralized approach and decentralized approach; centralized approached constituted by government and partner stakeholders. In Bangladesh REB and BPS are the main organization for rural electrification. The decentralized approach formulated by both top-down and bottom-up concept, standalone PV system, SHS, and renewable integrated hybrid mini-grid the best example in Bangladesh. The approach follows up and development of rural electrification in Bangladesh considered;
(1) Extending and intensifying the central grid
(2) Deploying off-grid technologies (off grid mini-grid, standalone MG, bottom up swarm electrification)

To implement the rural electric cooperative concept in Bangladesh, a central statutory agency called the Rural Electrification Board (REB) was formed by the government. The REB was given the responsibility of organizing the rural electric cooperatives (Palli Bidyut Samity, PBS); it employed managers to oversee the financial and administrative activities of the cooperatives. According to the World Bank manifesto, to bring most of the people electrifying under project "Rural Electrification and Renewable Energy Development" which mainly deployed by PV system [43].

A. Features of Rural Electrification

Before 1977, the government-owned Power Development Board (PDB) was the sole organization providing electricity throughout the country, without there being any special emphasis on rural areas. This actually left rural areas a very little chance to get access to electricity, and so, given this situation, the country launched the Rural Electrification Program (REP), which exclusively targets rural areas. The features of rural electricity in Bangladesh characterized by low voltage loads and distributed medium voltage lines. The power supply is unreliable and about 6 to 8 hours per day and phase imbalance. Average rural electric loads from 5 kW to 20 kW per village, and load factor around 0.2 to 0.3 (average demand/maximum demand). The load consumption in the households in rural areas are predominantly lighting, agricultural pumping, and mobile charge. The grids in a rural region often weak and high peak demand during evening lighting and summer agricultural pump. To implement the rural electric cooperative concept in Bangladesh, a central statutory agency called the Rural Electrification Board (REB) was formed by the government. The REB was given the responsibility of organizing the rural electric cooperatives PBS (Palli Bidyut Samity); it employed managers to oversee the financial and administrative activities of the cooperatives.

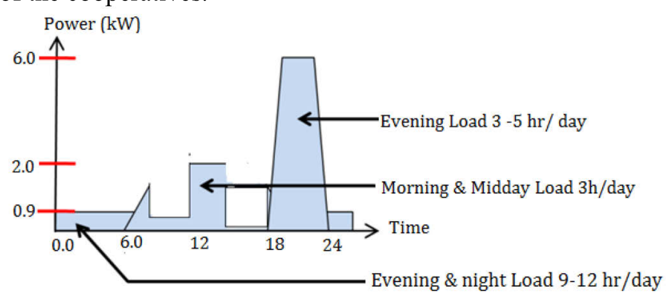


Figure 4: Typical Household Load Profile

B. Electric Energy Consumption Profile

In the modern epoch, electricity is the fundamental infrastructural input for economic development. Electricity is the flexible form of energy that drives development factors including industrialization, extensive urbanization, and intensification of living standards and modernization of agricultural sector. In Bangladesh Electricity is a major source of energy to meet the industrial and agricultural sector, both of these sectors contribute to 50.3 % of country's GDP [35]. Historically, Bangladesh is standing at overwhelmingly electricity generation by natural gas-based. According to the estimation of IEA, 1,400 MW electricity generation from 400 million cubic feet of natural in each day (IEA, 2014). In Bangladesh, natural gas supplied for consumption from two sources; state owned Petro-

Bangla, which contribute 99.4 % and international oil companies (IOCs) which account for 0.5 % of total supply.

Customer Category	Unit Price (tk/kWh)*
Category A: residential	
Life Line: from 1 to 50 unit	3.33
First Step : From 1 to 75 unit	3.80
Second Step : From 76 to 200 unit	5.14
Third Step : From 201 to 300 unit	5.36
Fifth Step: From 401 to 600 units	8.70
Sixth Step: Above 600 units	9.98
Category B: Agricultural pumping	3.82
Category-C : Small Industries	
Flat Rate	7.66
Off-Peak Time	6.90
Peak time	9.24
Category D: Non-Residential	5.22
Category E: Commercial and Office	
Flat Rate	9.80
Off-Peak Time	8.45
Peak Time	11.98

80 tk= 1 US $

IV. Renewable Energy penetration in Bangladesh

According to IEA Energy Access to comply the rural electrification, household having reliable and affordable electricity to clean cooking facilities, first electricity connection, and increasing level of electricity consumption over time as regional average. Bangladesh is the most potential country for renewable energy, significantly increases the number projects to meet the electrical energy throughout the country. The most existing form of renewable energy experienced in Bangladesh considering PV based off grid system including SHS, nano-grid, and mini-grid, where biomass also have high portentous to integrated significantly. With increasing both life and social standards urbanization is rapidly growing in developing countries, as comply urbanization growth electricity demand also increases promptly in Bangladesh. GOB has set target about 90 % electricity access across the country by 2018 [36] , to meet this vision innovative rural electrification integrated renewable energy is the best solution followed by the recent experiences, and achieving the target 2018 by connecting 450,000 households per months by 66 % SHS, and hybrid power system with renewable sources.

Although Bangladesh is the seven largest natural gas producer country among Asia, about 56% of gas consumption as the primary source of energy. As high dependency on natural gas, and experiences shortage of gas supply. The regular peak demands 5500 MW, but only 4000 MW of electricity produced by the conventional power generation system in 2007 that causes rolling electricity blackout. Remote areas and rural villages are the major mechanisms of holistic society; the development of socio-economy and environmental prominence in Bangladesh depends on productivity, and the productivity depends on access to energy. But the true reality is the government of Bangladesh not frequently involves for rural development including rural electrification due to some geographical constraints. In figure 7 represents, the electricity access increasing rapidly from 2000 to 2015.

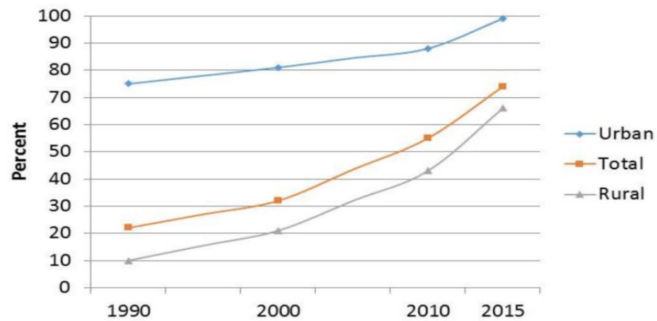


Figure 5: Change in Access to Electricity, 1990-2015

Electrifying in rural areas by conventional electrification system is expensive due to households are situated scattered and remote, and consumption rate low compare to urban electrification. Hence, no-electrified remote areas and poor villages electrifying by the conventional basis not promoted and focused. Consequently, it is urgent for the development of social life in Bangladesh by the availability of a reliable, adequate, and reasonably priced source of energy that uninterrupted balance of electricity supply.

Many countries and cities have already moved towards low carbon and clean energy transformations. Such as in Germany, for instance, is undertaking the 'Energiewende', an economic watershed that aims to produce 80 % of its electricity from renewable by 2050 [37]. Harnessing clean, renewable, and more efficient energy solutions will contribute not only to tackling a country's or community's energy challenges but also to the target of limiting global temperature rise to two degrees Celsius. As it is, a significant amount of GHG emissions are generated from energy production, thus tying sustainable energy directly to the climate change negotiations. Bangladesh today faces a different future than it did decades ago when abundant natural gas seemed to be the key to prosperity. At the same time as the centralized grid-based electrification has been the most common approach, decentralized renewable energy options especially, PV(photovoltaic) systems has also been adopted, especially for areas where it is techno-economically not feasible to extend the electricity grid.

These off-grid communities are generally small, consisting of low-income households with characteristics that may have been economically unattractive to electricity distribution companies to extend the grid. Small-scale renewable energy options, such as a solar home system (SHS) and biogas plants, have evolved as promising alternative for providing electricity to these disperse areas [38]. Other renewable energy options, such as wind energy and hydropower, have little potential to contribute to rural electrification in Bangladesh. Among the renewable technologies, the SHS option has accounted for the major share (80 %) of off-grid technologies in Bangladesh [39] [40] [41]. Bangladesh started its intensive rural electrification program in 1977 when only 10 % of its total population was connected to a grid. The country adopted a rural electric cooperative (REC) concept from the National Rural Electric Cooperative Association (NRECA), which had successfully electrified rural America in the 1930s [42]. According to the World Bank manifesto, to bring most of people electrifying under project "Rural Electrification and Renewable Energy Development" which mainly deployed by PV system [43].

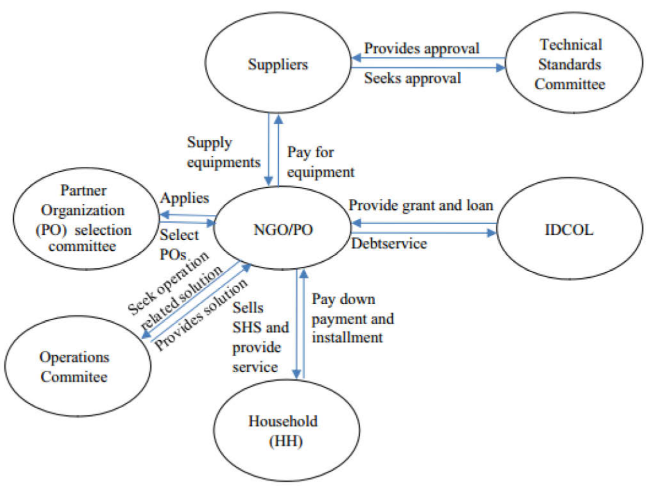


Figure 6: Institutional development for off-grid program

Amongst 49 partners' organization, IDCOL has developed a competitive market for Solar PV system without any geographic constraints by offering solar incentives; SHS installation, PV system with battery and charge controller supplies across the country [44]. Achieving quality and reliability of electricity supply is an important factor for each region, enhancement of reliability factor in integrating intermittent renewable energy like solar and the wind no choice except diesel generators, issues highlighted by (Foster and Steinbuks, 2009), estimates power system that generators owned compensated by 6 % of total capacity in Sub-Saharan Africa and other low-income countries up to 20 % [45]. Renewable electrification inspiring by the institutional framework in Bangladesh present in figure 8. Since renewable energy emerging in the power system of Bangladesh, the capacity gained 78 MW until 2012 which about 95 % of solar energy [46]. To comply the master plan, targeting 30 million of population electrified by off-grid system by 2016 which is about 18 % of the total rural population, whereas the number was about 15 million in 2013.

A. Biomass Potential

It is proved that Bangladesh has significant potential in biomass and biogas. Bangladesh is a tropical monsoon region, and agricultural is the main income for people who are living in the rural areas. Agricultural waste provides an enormous amount of biomass resources' assimilate with animal waste, household waste, and MSW which utilized to produce a large scale of electricity. Biomass generation system offers a number of advantages, mainly sources in low cost but high in energy efficiency compare to other fossil fuel, which reduces fuel costs. Besides electricity generation, biomass waste also affords fertilizer simultaneously. In Bangladesh gas is the main source of electricity production, according [47] about 88.8 % electricity generated by domestic gas, and a big part of electricity generation from imported furnace oil. In Bangladesh, from agriculture produces rice, wheat, maize, coconut, vegetables, jute, sugarcane, etc. About 46 % biomass energy sources from rice, straw, rice, husk, jute stick, sugarcane [48]. Most of the households in Bangladesh produces their vegetables and summer and winter accounted 48.16 % and 51.84 % respectively in the year 2011 [49].

Power generation from biomass gasification is reasonably novel in Bangladesh and favorable technology. Electricity generation by biomass gasification can be solved our day to day problem at an immense scope. Eventually, the purpose of rural electrification which is the expression of grief need of Bangladesh. In addition to producing electricity, it is advantageous to the agricultural and industrial expansion and production. It is almost impossible without rural electrification to meet the Bangladesh Government vision of ensuring access to reliable and affordable electricity for energy security-2020. Biomass and natural gas are the major sources of energy in Bangladesh, whereas 70 % biomass energy consumption of total energy consumption [39]. Biomass encompasses of agricultural residues in Bangladesh mainly rice, maize, wheat, coconut, groundnut, bean, vegetables, jute, and sugarcane etc. About 46 % of total Biomass energy has produced from agricultural crop residues. Rice is the main agricultural crop, and 70 % of rice husk energy is consumed. At present, NGOs are promoting small scale biomass system for clean cooking and electricity generation. There are two minor projects which supported by IDCOL those generating 200-300 kW by using poultry litter, moreover, the studies also suggested that up to 800 MW electricity by poultry waste litter. At present 15.00 tons of poultry litter produced each day, and a small fraction being used recycle. About 47 tons of waste expected, will be produced in 2025. In Bangladesh another available but significant raw material for biomass production rice husk, several search has shown that up to 400 MW of electricity can be generated single-handedly by rice husk.

B. Photovoltaic Potential

Bangladesh is blessed with enormous solar potential, as solar insolation. The average solar energy incident from 4 kWh/m²/day to 6.5 kWh/m²/day, with average 10.5 solar hours and about 300 clear sunny days. By the combination of a solar cell in PV module, under standard test condition (STC) module produces DC electricity at range 100 W to 400 W. In (figure 9) shown, clear bright sunlight, except June and July, average 7 to 9 h operates rest 10 months to produces solar energy. In figure 2-10, represents monthly average solar irradiation in different regions in Bangladesh.

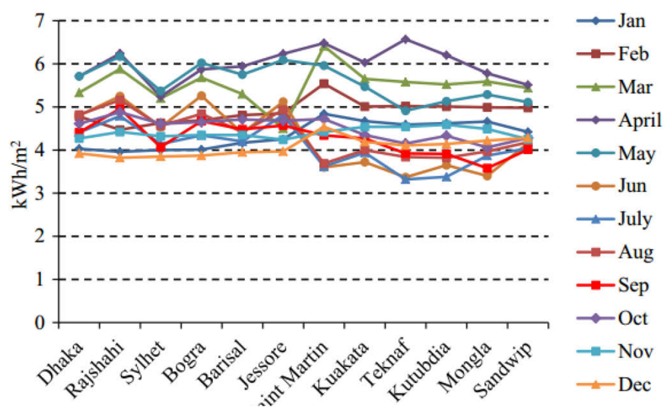


Figure 7: Solar Irradiation of different areas in Bangladesh

C. Solar Home System in Bangladesh

Solar sources and SHS has experienced a great success in Bangladesh, particularly the improvement of rural electrification. Currently, about 42 % of people have access electricity and per capita consumption of electricity is about 133 kWh in 2005 [52], which is the lower comparatively other developing countries. Nevertheless, the imbalance power supply makes a big difference between demand and supply, which makes load shedding. Started early 1980, PV flourished across the country and the success factors focus on; (i) Rural Areas electrified which are not yet accessible into the main utility grid. (ii) Remote areas where electricity access is almost impossible. (iii) Insufficient power supply.

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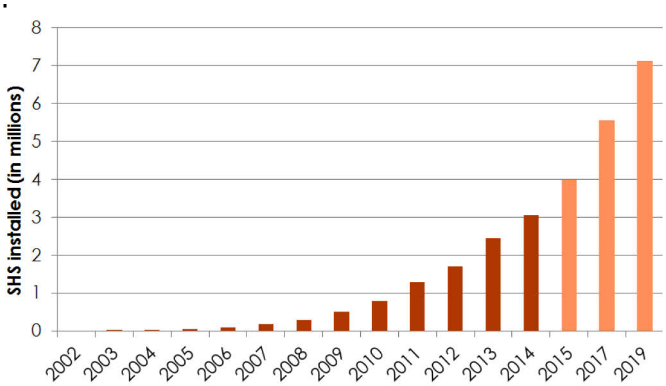

Figure 8: IDCOL SHS Program and Growth rate [56]

SHS generated electricity mainly used in rural households' loads including low power devices, CFL or LED lights, TV, mobile charger [53]. Bangladesh annual variation of inclination of the sun, measured from the vertical varies from 0 to 46 degrees between the summer and the winter. Summer days are longer, around 14 hours, with average sunshine more than 6kW-hr/day on clear sunny day. Although winter days are shorter around 10 h, still there is more than 4.5kW-hr/day of insolation on a clear sunny day. Solar Home System (SHS) are stand-alone photovoltaic systems that offer a cost effective mode of supplying power for lighting and appliances to remote off-grid households. In remote areas, which are not connected to the grid; SHS can be used to meet remote household's energy demand. In Bangladesh, SHS usually at a rate of 12 V DC and provide power for low power DC appliances including lights, TV, mobile charger, for about four to five hours. In developing countries like Bangladesh, where the national grid extension is not economically and technically feasible, an array of PV cells is used to build SHS. The main components of SHS include a solar panel, battery and a charge controller which can be operated with minimum training [54]. Over the past decade, since the Bangladesh government launched a rural electrification program supported by World Bank and other international aid bodies, the number of off-grid installations in the country has rocketed. In 2002, installations rates stood at 7000; today the figure has exploded to nearly 2 million and continues to count, with average installation rate now topping 80,000 per month [55].

IDCOL with other partner organization financed by World Bank 3357609 SHSs established until October 2014, and the numbers increase intensely present in (figure 2-11). The capacity achieved by SHS about 150 MW in the year 2013-2014, and growth rate increases about 185 %from the previous year. In 2015 the growth rate increases to 300 % and capacity raised 234 MW electricity generation potential from SHSs [57]. Generally distance between SHS about 2 to 2.5 meter, where most of the system capacity configured with 60 WP. As shown in (figure 2-11), SHS program promoted to increases more than 3.7 million by May 2015 [56], about 98 % of SHS installed through IDCOL [58], and additional 70,000 SHS being installed every month, and targeting more than 6 million more SHS by 2016 [59].

V. Innovation Approach for Rural Electrification

To achieved the Millennium Development Goals (MDG), electrification across nationwide is one of the main topology widely believed contribution, renewable sources deploy to sustainable development which leads to improvement of environment and fosters of socio-economic life. In the modern time, only 11 % of people have the access electricity in the Sub-Saharan countries [60], whereas in Bangladesh about 40 % of households have the access electricity [61] and the improvement rate of electricity through SHS system and bottom-up swarm electrification successfully experienced in Bangladesh past decades. The households and communities are far away from the main grid and grid extension are not always cost effective due to infrastructure and insufficient power supply.

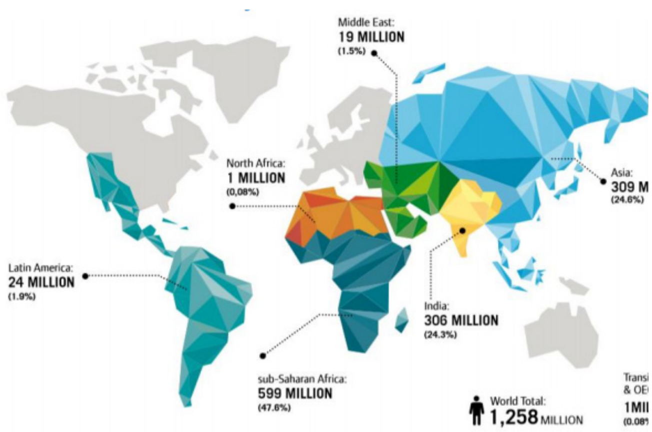

Figure 11: Word wide electricity access through Rural Electrification [62]

According to the authors' of [63] suggested, DC microgrid configured by several distributed generation such as SHS and from a local grid that might connect to the main grid. A mini-grid can be configured by local distributed generation system and the distributed generation sources' considering along with renewable resources such as PV, biomass, wind. According to swarm electrification concept, neighboring households are assimilating in an intelligent network where scheme allows sharing their information about supply, demand, and battery status within. To achieve this network by sharing electricity among participants within the scheme, consequently swarm network have the ability to integrate with legacy based where participants have the ability to produce electricity and consumption simultaneously, in order to propagate without or with limited number single centralized unit which has the ability to function independently may be called nano-grid. It is obverses that a sunny day an SHS in Bangladesh does not utilized their own capacity respect to their lords connected within the system, and 30% surplus electricity available for others [64]. Tier based Swarm concept explain in figure-13 and figure-14, tier-1 represents an SHS configuration and the loads consumption, self-generated electricity from PV panel. Tier -2 and tier -3 countenance SHS and BHS connected and formed a DC cluster, and tier -4 cluster grid also allow to connect to the grid to sellback surplus electricity. The major strategies for rural electrification to access electricity for all, some studies expressed only about 30 % of rural areas electrified by the centralized grid, whereas 70 % people can be electrified by the small scale nano-grid or microgrid [65].

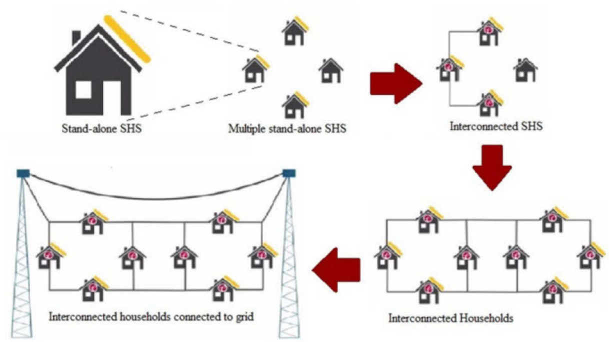

Figure 2: Swarm Electrification concept and stepwise approaches [66]

VI. Reforms and policies towards Renewable Energy

Declining the fossil fuel along with natural gas, the electricity production reduces whereas demand increases day by day. GOB has restricted and privatized the electricity generation sector by national Energy policy (NEP) in 1996. The major target of the policy to increase the power generation to meet the desires present and future demand which adopted by following policies:

I. Harnessing solar potential, and dissemination of RET in both urban and rural areas
II. Enable and encourage facilitate public and private sector investment towards RE projects
III. Development of sustainable energy system to substitute non-renewable sources
IV. Facilitating renewable energy at every level of energy including households to commercial and industrial

The national Energy Plan (NEP) envisions 5 % pf total renewable generation from renewable sources, and by 2020 achieved by 10 % energy from renewable.
Bangladesh Power Development Board (BPDB) imposed the bulk tariff for electricity consumption for distribution companies including Dhaka Electric Supply Company (DESCO), Dhaka Electric supply Authority (DESA), West Zone Power Distribution Company (WZPDC), Dhaka Power Distribution Company (DPDC), and Rural Electrification (REB). The distribution companies are working in the urban areas and REB with 77 rural electric cooperatives Palli Bidyut Samity (PBS) working for electrification in villages and remote areas.

VII. Conclusion

It is clear that most of the countries including low-income and developing countries GDP affected by the level of energy consumption, and per capita 0.23 % GDP increases by consuming 1 % of per capita energy consumption. The growth rate of electricity has increased by 5.5 % in the fiscal year 2006-2007, which rapidly increased to about 13.2 % in the fiscal year 2012-2013. Likewise, the GDP of Bangladesh has increased at the rate of 6.8 % in the fiscal year 2012-2013 from 2006-2007 observed at rate 6.15 %. Bangladesh is the fast growing developing country, socio-economic, industrialization, other development booming while demanding of electricity increases day by day. Currently, power sector of Bangladesh produces 7,445 MW by 2012, and 8002 MW by 2016 along with different government entities and non-government company working together to meet the electricity demand. Almost 72.42 % of total electricity generated from natural gas in the fiscal year 2013-2014, and on the other side, the renewable penetration only about 2.5 % which is the insignificant comparison to global power generation.

In the present time Bangladesh is one of the market leader of SHS, and standalone PV system. In Bangladesh average 4 to 6.5 kWh/m^2 solar irradiation, and Maximum amount of solar radiation is available almost each month except December-January, however, 300 high sunny days suggested solar generated system like standalone PV system, and SHS. IDCOL and other 47 partner organizations (POs), NGO working together to installing 3 million SHS by 2013 and targeting almost 7 million by mid of 2018.

The conventional power system is expensive to configure and present demand is lagging behind from the continuous power supply to electrification, especially for electrifying rural and remote areas. Notwithstanding, the conventional trends to generates electrical power from the top-down grid, and author convinced to follow up the concept of bottom-up swarm electrification would be the best solution for electrifying rural areas in developing countries. A robust grid can be formed amongst hybrid power system which configures with integrating distributed renewable sources and the backup diesel generator that highly efficient and reliable in the remote areas.

Currently, about 55.41 % of rural areas electrified by REB and cooperative organization PBS, whereas 5.05 million households connected to the grid. Yet 45 % of rural areas not electrified by REB which government owned company, but IDCOL and others POs working together to achieve Millennium Development Goad (MDG) and "Vision 2021" simultaneously, about 94 % households decreases about 1.7 liters of fuel (kerosene) consumptions compare to those not connected to the grid, average 90,000 households connected to the grid. During summer, the number of new households slightly increased to 300,000, and to achieve 100 % of electrification about 450,000 new households need to connect to the grid by 2018. By the successful SHS program along other biomass integration, and enrichment of electric power generation Bangladesh has achieved almost 11000 MW electricity by 2014, but still 40 % of population living without access to electricity.

VIII. References

[1] IEA, "Addressing the Electricity Access Gap," World Energy Outlook 2009, Paris, 2010.

[2] UNDP, "Human Development Report," 2008. [Online]. Available: http://hdrstats.undp.org/indicators/211.html. [Accessed 29 feb 2016].

[3] H. K. Alimul, R. Anisur and M. Moniruzzaman, "Source Management of A Hybrid DC Micro Grid in Rural Area of Bangladesh," International Conference Materialsm electronics and information engineering, ISBN 978-984-33-8940--4, 2015.

[4] H. Najmul and K. D. Barun, ""'Analysis of cost,Energy and CO2 Emission of Solar Home Systems in Bangladesh," International Journal of Renewable Energy Research , 2012.

[5] BD-Research, "Electricity Senario in Bangladesh," 2012. [Online]. Available: ⟨http://www.bdresearch.org.bd/home/attachments/article/799/Electricity%20Scenario%20in%20Bangladesh.pdf. [Accessed 28 Feb 2016].

[6] M. Mondol, W. Boie and M. Denich, "Future demand scenarios of Bangladesh Power Sector," Energy Policy Report 38, 2010.

[7] H. Ahsan and C. Supachart, "Utilization of Solar and Biomass for Rural Electrification in Bangladesh," in *International Conference and Utility Exhibition* , Pattaya, Thailand , 2014.

[8] Regional Energy Security for South Asia: Regional Report , "South Asian Regional Initiative for Energy Integration," 2014. [Online]. Available: http://www.sari-energy.org/. [Accessed 30 Oct 2015].

[9] Asian Development Bank, "Key Indicators for Asia and the Pacific," Asian Developlment Bank Report, 2011.

[10] JIKA, "Bangladesh Power System Master Plan (PSMP)," Tokyo Electric Power Co. Ltd., Tokyo, 2010.

[11] BBS, "Statistical Yearbook of Bangladesh," Bangladesh Bureau of Statistics, Governtment of Bangaldesh, Dhaka, 2003.

[12] BPDB, "Power Generation Report," Bangladesh Power Developmenet Board , http://www.bpdb.gov.bd, 2013.

[13] IAEA, "Country Power Profile Edition,," Available: http://www-pub.iaea.org/, 2013, [Accessed on 27 June, 2015].

[14] L. Chanda and G. Hossain, "A green Economy in the Context of Sustainable development and proverty Eradication: What are the IMplications for Bangladesh?," *Journal of Economics and Sustainable Development,* vol. 5, no. 3, pp. 119-131, 2014.

[15] R. Plunkett, A. Newton and B. J. Wagenhauser, Bangaldesh, Victoria, Autralia : Lonely Planet Publications Pty Ltd. , 2000.

[16] N. Hosnay, "Acquisition of Sustainable Economic Growth through Proper Utilization of Renewable Energy Sources – A Study on Various Aspects, Challenges

andProspects of RE in Bangladesh," NUB, ET-P11, Dhaka , 2013.

[17] Generation-Report, "Owner Wise Daily Generation Report," 2014. [Online]. Available: http://www.bpdb.gov.bd/bpdb/index.php?option=com_content&view=article&id=193&Iption=com_content&view=article&id=193&I. [Accessed 12 Dec 2016].

[18] A. Khairul and A. Husnain, "Power Crisis & Its Solution through Renewable Energy in Bangladesh Cyber Journals: Multidisciplinary," Journals in Science & Technology. Journal of Selected Areas in Renewable and Sustainable Energy , 2011.

[19] Bari,MN; Hall, DO; Lucas, NJD; et. al., "Biomass Energy use at the Ousehold Level in two Villages of Bangladesh: Assessment of field Methods," *Biomass Energy ,* vol. 15, no. 2, p. 171–180, 1998 .

[20] A. Report, "Annual Report of 2012-2013," Bangladesh Power Development Board (BPDB), Dhaka, Bangladesh .

[21] Asif, Islam; Maidul, Islam; Sanchita, Ghose; et al, "A Review on Electricity Generation and Evacuation in Bangladesh," Energy and Power: academic research, 10.5923/j.ep.20150501.02, Dhaka, Bangladesh, 2015.

[22] B. Report-2014, "Daily Power Generation Report-," Bangladesh Power Development Board, Dhaka, Bangladesh, 2014.

[23] H. Gunatilake and D. Ronald-Holst, "Energy Policy Options for sustinable Development in Bangladesh," *ADB Economics Working paper series ,* pp. 9-12, November 2013.

[24] R. Mustafizur, "Electricity Scenario in Bangladesh," Unnayan Onneshan-The Innovators , Dhaka, 2011.

[25] BPDB, "Power Generation Report," angladesh Power Development Board (BPDB), 2015. [Online]. Available: http://www.bpdb.gov.bd/bpdb/. [Accessed 12 Dec 2015].

[26] Power-Division, "Bangladesh Energy Status Report," Power Division. Ministry of Power, Energy and Mineral Resources. Government of the Peoples Republic of the Bangladesh, 2014. [Online]. Available: ttp://www.powerdivision.gov.bd/user/index. [Accessed 12 Dec 2015].

[27] Annual-Report, "Power Grid Company of Bangladesh (PGCB) 2012-2013," PGBC, Dhaka, Bangladesh , 2014.

[28] D. Palit, "Solar energy programs for rural electrification: Experiences and lessons," *Elsvier: Energy for sustaiable development ,* no. 17, p. 270–279 , 2013.

[29] B. Douglas and F. Gerald, "Rural Electrification in the Development World: a Summery of Lessons from Successful programs," World Bank Energy Sector Management Assistance Programme (ESMAP) , Washington DC, 2004.

[30] D. Palit and A. Chaurey, "Off-grid rural electrification experiences from South Asia: Status and Best Practice," *Energy for Sustainable Development,* pp. 266-267, December 2011.

[31] W. Bank, "Financing for Rural Electrification and Renewable Energy Development Project: Bangladesh (Project Paper Number 64347-BD)," Word Bank , Washington DC, 2010.

[32] BBS, Report of the Household Income & Expenditure Survey, Bangladesh Bureau of Statistics: Dhaka, Bangladesh , 2010.

[33] Power-Division, "Bangladesh Power Sector: An Overview," Bangladesh Power Development Board , September 2015. [Online]. Available: http://www.bpdb.gov.bd/bpdb/. [Accessed 12 Feb 2016].

[34] C. Paul, "Infrastructure, rural electrification and development.," *Energy for Development ,* no. 15, pp. 304-312, 2011.

[35] M. Mahedi, "Electricity Consumption and Economic Growth," *Global Journal of Management and Business Research,* vol. 12, no. 11, 2012.

[36] SREP-Bangladesh, "Scaling Up Renewable Energy in Low Income Countries (SREP): Investment Plan for Bangladesh," Sustainable & Renewable Energy Development Authority , Dhaka, Bangladesh , 2015.

[37] M. Martinez Solaiman , "Inter Press Service," NewS Agency , 08 July 20015. [Online]. Available: http://www.ipsnews.net/2015/05/opinion-clean-energy-access-a-major-sustainable-development-goal/. [Accessed 8 07 2015].

[38] World Bank , "Designing Sustainable Off-Grid Rural Electrification Projects:," The World Bank, Washington DC, USA , 2008.

[39] I. AKM Sardul, I. Mazharul and R. Tazmilur, "Effective renewable energy activities in Bangladesh," *Renewable Energy,* no. 31, pp. 677-688, 2006.

[40] M. Z. Rahman, "Multitude of progress and unmediated problems of olar PV in Bangladesh," *Renewable and Sustainable Energy Reviews,* no. 15, pp. 466-473, 2012.

[41] M. M. Rahman and J. V. Paatero, "A methodological approach for assessing potential of sustainable agricultural residues for electricity generation: South Asian Prospective," *Biomass and Bio Energy ,* no. 47, pp. 153-163, 2012.

[42] NRECA, "Guides for Electric Cooperative Development and Rural Electrification," NRECA International, Ltd , Washington, DC, USA, 2004.

[43] E. Cecelski, "[10]. Cecelski,E, "Enabling equitable access to rural electrification: urrent thinking and major activities in Energy," World Bank, Washington DC, 2000.

[44] IEG-Report, "Rural Electrification and Rnewable Energy Development," Workd Bank, Dhaak, Bangladesh , 2014.

[45] PRODUSE, "The Impact of Electricity Access on Economic Development: A literature Review," Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH, Frankfurt, Germnay, 2013.

[46] IDCOL, "Renewable Energy Status in Bangladesh," Infrastructure Development Company Limited , 2014. [Online]. Available:

http://www.idcol.org/prjshsm2004.php. [Accessed 12 Dec 2016].

[47] BBS, “Statistical yearbook of Bangladesh 2008,” Bangladesh Bureau of Statistics; 2009, Dhaka, Bangladesh , 2009.

[48] M. Islam, M. Islam and M. Beg, “Renewable energy resources and technologies practice in Bangladesh.,” *Renewable Sustainable Energy Rev ,* vol. 12, p. 299–343, 2008.

[49] A. Huda, A. Mekhilef and A. Ahsan, “Biomass energy in Bangladesh: Current status and prospects,” *Renewable and Sustainable Energy Reviews,* vol. 30, p. 504–517, 2015.

[50] M. Motin, M. Zaman and M. Sheikh, “Energy efficient modelling of solar wind hybrid power system for a tourist island,” *Int J Adv Renew Energy Res (IJARER),* vol. 1, no. 1, 2013.

[51] Hasan, AM; Khan, MF; Dey, A; et al, “Feasibility study on the available renewable sources in the island of Sandwip, Bangladesh for generation tion of electricity,” *In: Proceedings of the international conference on developments in renewable energy technology (ICDRET),* p. 1–4, 2012.

[52] PSMP, “Power System Master plan Update,” Ministry of Power, Energy and Mineral Resources, Dhaka, Bangladesh , 2006.

[53] R. Paleta, A. Pina and C. Silva, “Remote autonomous energy systems project: towards sustainability in developing countries.,” *Energy,* vol. 48, no. 1, pp. 431-9, 2012.

[54] S. Islam, “Photovoltaic Technology for Bangladesh,” in *Bangladesh University of Engineering & Technology, Dhaka and Center for Renewable Energy System Technology, Leicestershire*, Infield, 2001.

[55] B. Willis, “Friday Focus: How Bangladesh become the world's biggest off-grid solar user,” PV-tech, 05 July 2013. [Online]. Available: http://www.pv-tech.org/friday_focus/friday_focus_how_bangladesh_became_the_worlds_biggest_domestic_off_grid_pla. [Accessed 22 July 2015].

[56] IDCOL, “Solar Home System Program and Projects,” 2014. [Online]. Available: http://idcol.org/home/solar. [Accessed 30 Dec 2015].

[57] BPDB, “Power Divsion of Bangladesh,” Bangladesh, Renewable energy in Bangladesh , 2015. [Online]. Available: http://www.powerdivision.gov.bd/user/brec/49/89. [Accessed 02 Feb 2016].

[58] Khandker, S.R; Samad, H.A; Sadeque, Z.K; et al, “Surge in Solar-Powerd Homes - Experience in Off-Grid Rural Bangladeseh,” The World Bank, Washington DC, USA, 2014.

[59] M. Islam, “IDCOL Solar Home System Program,” 2014. [Online]. Available: https://www.esmap.org/sites/esmap.org/files/ESMAP_SAR_EAP_Renewable_Energy. [Accessed 30 Dec 2015].

[60] Gunther, Bensch; Jochen, Kluve; Peters, Jörg, “Rural Electrifi cation in Rwanda–An Impact Assessment Using Matching Techniques,” RUHR Economic Paper , Dec 2010. [Online]. Available: http://en.rwi-essen.de/media/content/pages/publikationen/ruhr-economic-papers/REP_10_231.pdf. [Accessed 01 march 2016].

[61] IBRD-IDA, “Lighting Up Rural Communities in Bangladesh,” The World Bank, 15 Jan 2014. [Online]. Available: http://www.worldbank.org/en/news/feature/2014/01/15/lighting-up-rural-communities-in-bangladesh. [Accessed 02 Mar 2016].

[62] ECOWAS, “ECOWAS Renewable Energy and energy efficiency status report,” ECOWAS, 2014.

[63] Sarker, M.J; Asare-Bediako, B; Slootweg, J.Gp; et. al, “DC microgrid with distributed generation for rural electrification,” in *47th International Conference on Universities Power (UPEC)*, London, 2012.

[64] K. Hannes, “Hidden Resources in Solar Home Systems as the Base for Bottom-Up Grids. Proc. of the Int. Conf. Innovating Energy Access for Remote Areas: Discovering untapped resourc,” in *Proc. of the Int.Conf. Innovating Energy Access for Remote Areas: Discovering untapped resources*, Berkeley, USA, 2014 .

[65] OECD/IEA, “Energy for All: Financing Access to the Poor,” World Energy Outlook, Paris, France , 2011.

[66] Martina, Schafer; Daniel, Kammen; Noara Kebir; et al, “Innovating Energy Access for Remote Areas: Discovering Untapped Resources,” in *Proceedings of the International Conference, University Berkeley* , Berkeley, 2014.

Experimental Analysis of Linear Induction Motor under Variable Voltage Variable Frequency (VVVF) Power Supply

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Abstract. This paper presents the complete analysis of Linear Induction Motor (LIM) under VVVF. The complete variation of LIM air gap flux under 'blocked Linor' condition and starting force is analyzed and presented when LIM is given VVVF supply. The analysis of this data is important in further understanding of the equivalent circuit parameters of LIM and to study the magnetic circuit of LIM. The variation of these parameters is important to know the LIM response at different frequencies. The simulation and application of different control strategies such as vector control thus becomes quite easy to apply and understand motor's response under such strategy of control.

Keywords: *Linear Induction Motor, Variable Voltage Variable Frequency, Experimental, air gap flux density, blocked linor.*

1. Introduction

A linear motor can be obtained by cutting a rotary motor along it's radius from the center axis of the shaft to the external surface of the stator core and unrolling the cut motor to get a flat construction of (previously) annular stator and cylindrical rotor [1].

Since the stator and rotor both have finite diameters, hence their lengths in linear version will also be finite and hence machine with mere such a construction will obviously not be of practical use. This is because as any of the part (stator or rotor) start moving it goes slowly out of the influence of the other part and stops moving after some time when it comes completely out of influence of the other part. Hence it is necessary that either both the members be infinitely long-which is again not practical or at least one of the two members be very long and the other one is of some finite length [2-3].

The LIMs performance is affected by the conductor reactance, resistance and the construction of the secondary structure [4]. In the linear structure, the moving part which may or may not be the rotor of the induction motor is called as the 'linor'. In general terms, the part which we excite by electrical supply to windings is called as the 'primary' and the other part is called as the 'secondary'. The LIM has many merits in comparison to the rotary induction motor (RIM): higher ability to exert thrust on the secondary without mechanical contacts, greater acceleration or deceleration, less wear of the wheels etc. [5].The main advantage of LIM is its open magnetic structure gives us access to its air gap magnetic field very easily and measurements of this field can be carried out with search coil. Also the starting force measurements are easy to carry out with simple instruments such as spring balance placed horizontally and one end attached to a rigid support.

Recently the finite element modeling (FEM) approach has gained greater importance in modeling of LIM [6]. Many research has been done considering attraction force and transverse edge effect of LIM [7].

LIM finds tremendous application in transportation. Many countries has come up with transport network based on LIM [8-10]. Other application of induction motor beside transportation are in railway engines,

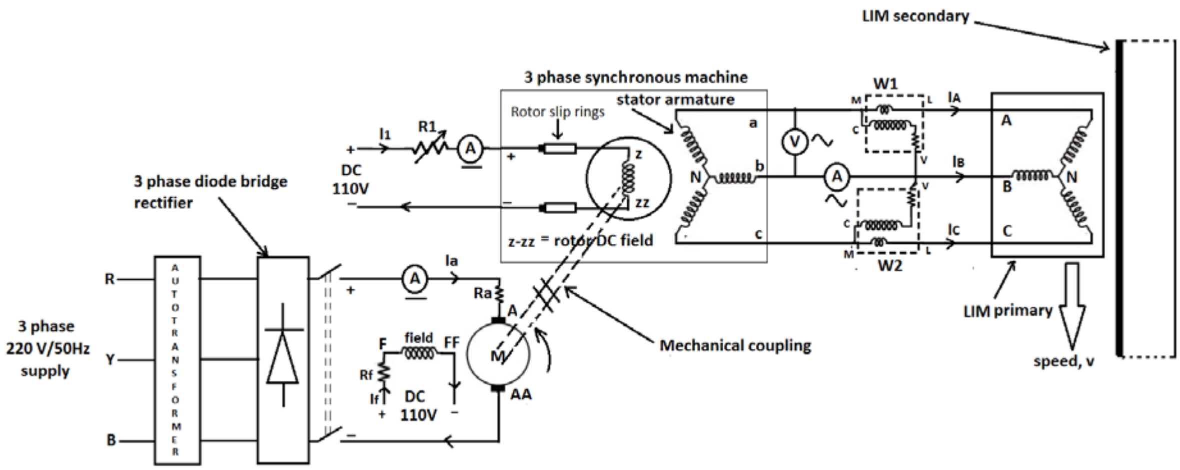

Fig. 1 Schematic connection diagram to obtain VVVF supply to LIM primary

self-excited induction generators for distributed generation in rural areas [11-13], etc.

This paper is organized as follows: Section 2 describes the experimental setup and procedure to obtain the VVVF supply and the methods used to measure the air gap flux density and starting thrust of LIM under 'blocked linor' condition. The experimental values of flux density and starting thrust under VVVF supply are plotted in section 3. Observations and conclusions from these plots are stated in section 4.

2. The experimental set-up to obtain VVVF supply:

The schematic connection diagram of the supply arrangement which is used to obtain VVVF supply for LIM testing is shown in figure 1.

In the above figure the mechanically coupled arrangement of a DC machine- synchronous machine set up has been done. The DC machine used was of the separately excited type. The field terminals of DC machine are marked as F-FF and the armature terminal are marked as A-AA as shown. R_f and R_a are the internal winding resistances of the DC machine field winding and armature winding respectively.

In the arrangement used for LIM testing, rated constant voltage was given to field winding throughout the testing. The armature was given DC supply through a 3 phase diode bridge rectifier .The AC input to bridge rectifier was given by means of a variac (or autotransformer) so that we can have smooth control over the armature voltage. Speed of the DC machine was varied by means of varying the bridge rectifier output through autotransformer.

An ammeter was connected in series with the armature so that the armature current can be observed and it can be maintained within the safe limit set up by rated armature current limit of DC motor.

The synchronous machine rotor DC field voltage can be varied by means of varying the variable resistance R1 connected in series with the DC rotor field. The rheostat for R1 is of appropriate current rating. The alternator's 3 phase armature output was given to LIM which is the regulated VVVF supply.

The ammeter connected to one of the armature phases will give the LIM phase current 'Iph' and also the alternator armature current can be observed so as to maintain it within it's safe limit specified by its rated value.

The LIM line voltage ($\sqrt{3}$ Vph) is obtained by voltmeter connected in parallel between any of the two phases as shown in Fig. (1). The real power input to LIM is measured by means of 'two wattmeter method'.

For the power factor of cos (∅),

3 phase Power input to LIM = W1+W2 = 3.Vph.Iph.cos (∅) (watts) (1)

i. Rating of different components:

a) DC machine specifications:

Armature rating and specification: 3.75 BHp, 110V, 32.6A, 1200 rpm, Ra =1 Ω
Field ratings: 110V, 1.8A, R_f = 61 Ω

b) Synchronous machine specifications:

Stator armature ratings: The stator armature has two sets of 3 phase output terminals which can be used at two different frequencies viz. 50Hz and 60Hz .The voltage and current ratings are shown in table 1 for these two frequencies:

Table 1: The voltage and current ratings at two frequencies.

Frequency F (Hz)	**Output, (KVA)**	**Line voltage (V)**	**Line current (A)**	**Speed (rpm)**	**No of poles, P**
50	3.0	130	13.3	1000	6
60	3.0	125	13.9	1200	6

The per phase armature resistance = 0.35 Ω
DC rotor field ratings: 110V, field DC winding resistance = 10 Ω
LIM specifications: 3 phase, 50 Hz, 1.5kW, 110V, Pole pitch=9.65 cm

ii. Method used for obtaining VVVF supply

Principle: The rotating DC voltage supplied rotor's field with speed Nr rpm induces voltage in the stator armature of synchronous machine. The magnitude of this induced voltage depends on the speed of rotation Nr rpm of synchronous machine and also the air gap flux produced by the DC supplied rotor i.e. the amount of current in the DC rotor winding. The frequency of the AC induced voltage depends on the rotor speed Nr of alternator.

Control Mechanism: To change the frequency of the output voltage , we increase the speed of the DC motor which acts as a prime mover for the alternator .The speed of DC motor is varied by 'armature voltage control' method by varying armature voltage using autotransformer. The main problem with this is that increasing the DC motor speed will increase the frequency as well as the magnitude of the alternator output voltage.

So the alternator rotor DC field is needed to be reduced so as to obtain the same voltage at higher frequency.

If, an alternator with P no of poles is rotating at a speed of Nr rpm, then output frequency f (Hz) of the armature voltage is given by,

$$f = \frac{P.N_r}{120} \text{ Hz} \quad (2)$$

In the air gap, constant flux φ Wb is set up by the DC field of rotor at standstill. If the rotor is rotating then, the flux φ linked with each phase is actually a time varying quantity φ(t) as viewed from the stator, and is given by

$$\varphi(t) = \varphi_{max} .\cos(\omega.t) \tag{3}$$

where ω =2πf rad/sec.
If the output armature voltage has frequency f Hz , then the instantaneous induced voltage in each phase of the armature having per phase no. of turns Tph and winding factor of Kw is :

$$E_{ph.a}(t) = \omega.Tph.\ \varphi_{max}.\cos(\omega.t).Kw\ (volts) \quad \text{(A phase induced voltage)} \tag{4}$$

$$E_{phb}(t) = \omega.Tph.\varphi_{max}.\cos\left(\omega.t - \frac{2\pi}{3}\right).Kw\ (volts). \quad \text{(B phase induced voltage)} \tag{5}$$

$$E_{ph.c}(t) = \omega.Tph.\varphi_{max}.\cos\left(\omega.t + \frac{2\pi}{3}\right).Kw\ (volts) \quad \text{(C phase induced voltage)} \tag{6}$$

As the armature windings are distributed at a spatial displacement of 120° in space w.r.t. each other, hence the induced voltages in each phase will be 120° phase shifted from one another as described by Eq. (4) to (6).

Hence, we have to always adjust both φ_{max} (by adjusting the DC current of the alternator rotor) and frequency 'f' (by adjusting armature voltage of DC motor) at a time if we want to achieve same voltage at different frequencies or vice versa.

iii. Advantages and disadvantages of this supply arrangement:

a) Advantages:

- This arrangement is the ideal and easiest method to obtain a constant V/f supply at different frequencies. From Eq. (4) to (6), it can be observed that if the DC current of alternator DC field is kept constant i.e. if φ_{max} is kept constant then if we neglect stator leakage reactance, stator winding resistance voltage drop of alternator and primary winding resistance and leakage reactance voltage drops in LIM, then for LIM, the induced voltage to frequency i.e. Eph/ ω ratio is constant at different frequencies ω rad/sec.
- This method is very rugged and robust method to obtain V/f as once the DC rotor current is adjusted at some value, then by just varying the autotransformer voltage, we achieve almost constant V/f across the load terminal at armature.
- More robust and easy to use than the PWM inverter.

b) Disadvantages:

- In running condition of alternator, as the load to armature increases, then the alternator speed reduces. To keep the alternator to run at same frequency irrespective of the armature terminals load variation, the alternator should be synchronized with the desired output frequency by some other alternator. This is somewhat tedious process because each time we want the different frequency then that time first of all that synchronization should be carried out and then the load is to be connected.
- This method is mostly suitable for the constant loads connected to the armature of alternator.
- The LIM at 'blocked linor' condition acts as a constant load and hence this method for obtaining VVVF supply suits best for such condition.

iv) Testing of LIM prototype by this setup:

In case of testing of LIM by using this setup, the measurement of starting thrust at 'blocked rotor' test can be easily carried out at different voltages and frequencies as load seen by armature of alternator is constant during 'blocked linor' condition.

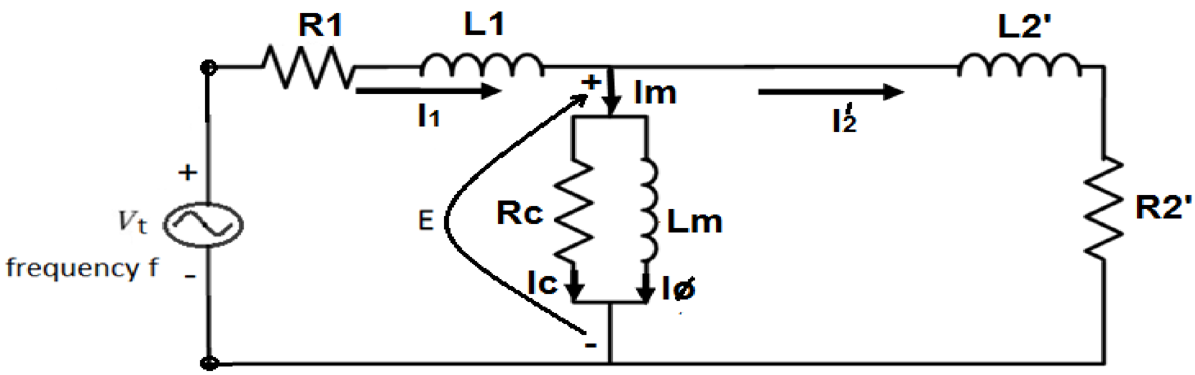

Fig. (2)Per phase exact equivalent ckt of LIM considering core losses at 'Blocked linor' condition

When LIM starts moving, the load seen by the alternator armature gradually reduces, hence because of this the speed of alternator Nr and hence armature supply frequency f increases and hence also the induced voltage as per Eq.(3) to (6) . As the secondary length of the SS-LIM prototype used is around 4 meters which is a short distance for LIM, there is no appreciable increase in the supply frequency f at running condition of LIM for this short distance of 4 metre. Hence, for the speed measurement on available setup of LIM prototype used, this method works sufficiently accurate.

To obtain voltages at low frequencies from alternator, the DC motor should be run at low speeds. At such low speeds if the DC field excitation of alternator is increased, the load to DC motor increases and it can increase to such extent that the DC motor armature current becomes more than the rated value i.e. DC motor can get overloaded if we try to get more magnitude of alternator output voltage at low frequencies. So there is a limitation on the maximum voltage that we can obtain from alternator at a given frequency. For operating voltages and currents of LIM at different frequencies, this setup is sufficient.

3. Measurement

i) Measurement of air gap flux at VVVF supply under 'Blocked linor' condition:

The flux density magnitude at a particular point on LIM primary is different than that of at other points at different locations because of edge effects, end effects, etc.

The following Fig. (3) shows the variation of maximum air gap flux Bmax vs LIM primary phase current at different supply frequencies. This air gap flux is measured by fixing the search coil at one specific particular point on the LIM primary iron core surface in the air gap.

As seen from fig (3) for the same primary phase current, the air gap flux density is reduced gradually. This is because, as we increase the supply frequency ω , the leakage reactance $X_{L1}= \omega L_1$ and hence the voltage drop across the primary leakage reactance becomes more and more prominent hence, the voltage across the magnetizing branch also goes on reducing and finally the magnetizing current is also reduced at increased frequencies as can be seen from the equivalent circuit of LIM as shown in Fig(2) .

Primary leakage reactance $=Iph.X_{L1}= Iph.\omega L_1$ (7)

We know that the magnetizing current is the main component of supply current which sets up the air gap magnetic flux. Hence, at increased frequencies, for the same applied voltage magnitude, as we have lesser magnetizing current, the air gap flux reduces.

ii) Measurement of starting thrust by spring balance at VVVF supply:

The fig. (5) shows the measurement of starting thrust (N) at 'blocked linor' condition by spring balance method vs primary phase current (A) at air gap = 0.7cm air gap at different supply frequency . From fig.(4), it can be observed that at same supply current ,as the supply frequency is increased, the stating thrust gets gradually reduced .This is because the reduction of air gap flux as observed from fig.(3) .

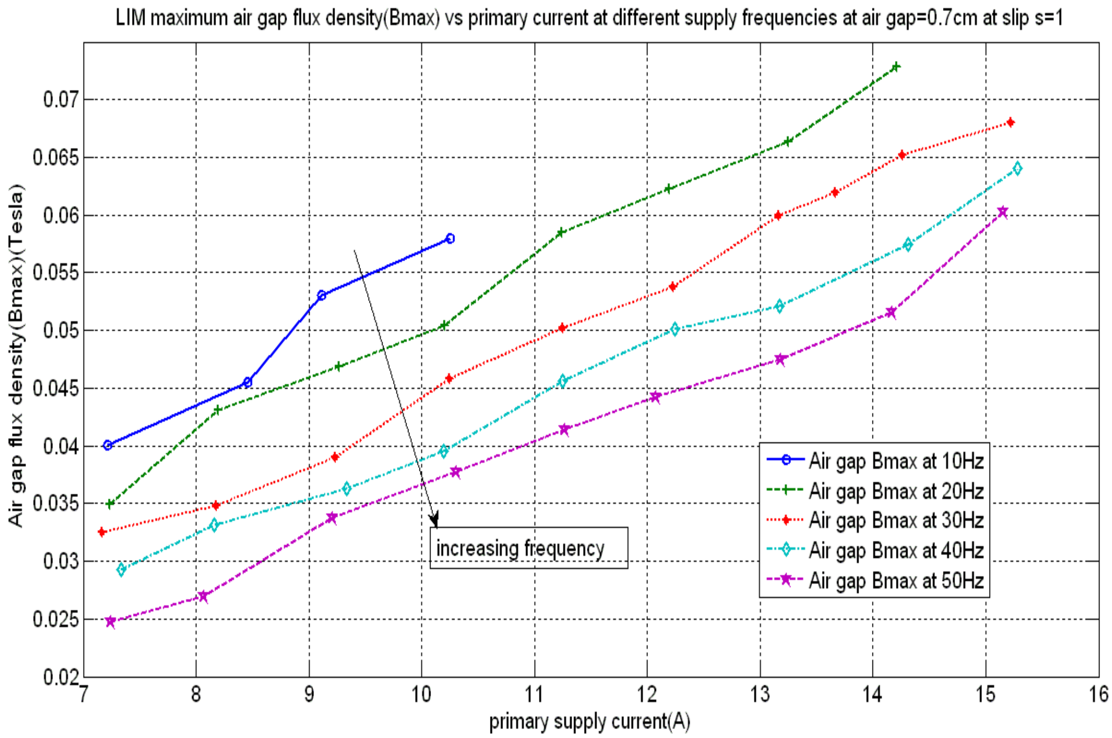

Fig (3). Maximum air gap flux density Y component Bmax (tesla) vs primary supply phase current (A) at different frequencies at 'blocked rotor' condition at 0.7 cm air gap

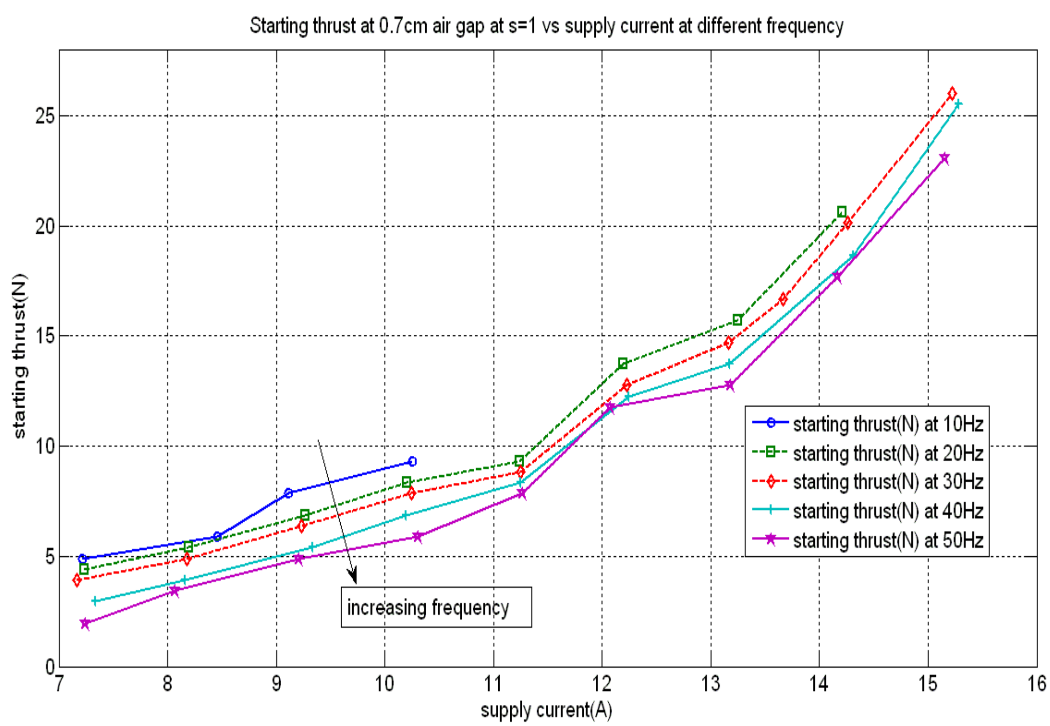

Fig (4). Starting thrust vs primary supply phase current (A) at different frequencies at 'blocked rotor' condition at 0.7 cm air gap

In phasor form, the force acted upon the LIM primary is, $\vec{F} = \vec{J_1} \times \vec{B}$ (N). (8)

As observed from Fig.(3), at different increasing frequencies, amplitude of $\vec{B}$ is reduced at same primary current Iph (i.e. at same primary linear current density amplitude $\vec{J_1}$) at different increasing frequencies. Hence it is obvious that as per Eq. (8), the starting thrust $\vec{F}$ will decrease at constant $\vec{J_1}$ and reduced air gap flux density $\vec{B}$.

4. Conclusion

In this paper an experimental analysis of linear induction motor under variable voltage variable frequency (VVVF) power supply has been done. This analysis is required keeping in mind the tremendous application LIM is having in transport nowadays. Detail discussion of the experimental setup is given in the paper along with its merit and demerit. Maximum air gap flux density Y component Bmax (tesla) vs primary supply phase current (A) at different frequencies as well as starting thrust vs primary supply phase current (A) at different frequencies at 'blocked rotor' condition is presented and discussed for better understanding of the subject.

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References

1) K.Venkatratnam, "Special Electrical Machines" Universities Press India Pvt. Ltd. (2009),
2) Wei Xu, Jian Guo Zhu, Yongchang Zhang, Zixin Li, Yaohua Li, Yi Wang, Youguang Guo, Yongjian Li, "Equivalent Circuits for Single Sided Linear Induction Motors" ,IEEE Transactions On Industry Applications, Vol. 46, No. 6, ,Pages.2410-2422 November/December 2010
3) Wei Xu; Jianguo Zhu; Youguang Guo; Yi Wang; Yongchang Zhang; Longcheng Tan, "Equivalent circuits for single-sided linear induction motors," Energy Conversion Congress and Exposition, 2009. ECCE 2009. IEEE , vol., no., pp.1288,1295, 20-24 Sept. 2009
4) B.-J. Lee , D.-H. Koo and Y.-H. Cho "Investigation of linear induction motor according to secondary conductor structure", IEEE Trans. Magn., vol. 45, no. 6, pp.2839 -2842 2009
5) Wei Xu, Jianguo Zhu, Longcheng Tan, Youguang Guo, Shuhong Wang, and Yi Wang, "Optimal design of a linear induction motor applied in transportation," in Proc. IEEE Int. Conf. Industry Technology, , pp. 791-795. Feb. 2009
6) S. C. Ahn , J. H. Lee and D. S. Hyun "Dynamic characteristic analysis of LIM using coupled FEM and control algorithm", IEEE Trans. Magn., vol. 36, no. 4, pp.1876 -1880 2000
7) A. K. Rathore and S. N. Mahendra "Simulation of secondary flux oriented control of linear induction motor considering attraction force and transverse edge effect", Proc. Int. Conf. Elect. Eng., pp.158 -163 2003
8) R. Thornton , M. T. Thompson , B. M. Perreault and J. Fang "Linear motor powered transportation", Proc. IEEE, vol. 97, no. 11, pp.1754 -1757 2009.
9) R. Hellinger and P. Mnich "Linear motor-powered transportation: History, present status, and future outlook", Proc. IEEE, vol. 97, no. 11, pp.1892 -1900 2009.
10) Wei Xu, Yaohua Li, Guangsheng Sun, and Jinqi Ren, "Performance study on high power linear induction motor in transportation," in Proc. Int. Conf. Electrical Machines and Systems, pp.1025-1027, Oct. 2007.
11) M. Tariq and S. Yuvarajan. Modeling and Analysis of Self Excited Induction Generator with Electronic load controller supplying static loads. Canadian Journal on Electrical and Electronics Engineering, 4(1), pp.9-13, 2013.
12) M. Tariq, S. Yuvarajan, and P. Wakode. Digital Simulation of Electronic Load Controller with Reduced THD for Self-Excited Induction Generator. IUP Journal of Electrical and Electronics Engineering, 6(4), p.36, 2013.
13) M. Tariq and S. Yuvarajan, Simulink Based Modeling, Analysis and Simulation of Self Excited Induction Generator for Use in Remote Areas. IU-Journal of Electrical & Electronics Engineering, 13(1), pp.1623-1628. 2013.