Research Journal of Applied Sciences, Engineering and Technology 7(19): 4137-4142, 2014
DOI:10.19026/rjaset.7.778
ISSN: 2040-7459; e-ISSN: 2040-7467

Submitted: December 18, 2013 Accepted: December 27, 2013 Published: May 15, 2014

Research Article

Reduction in Pollutants Emission by Increase in Renewable Penetration: A Case Study

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Abstract: For environmental friendly electricity supply system, the global utilization of Renewable Energy Resources (RES) and Distributed Energy Storage (DES) facilities is increasing rapidly. The environmental benefits possible when utilizing renewable power generation along with the conventional power production are analyzed here. Considerable amounts of pollutants emission from power generation based on fossil fuels can be reduced with high penetration of RES. The aim of this study is to increase the awareness on the benefits achieved by the utilization of renewable power. A generalized model for analyzing the impacts of renewable penetration on the amount of pollutants emission from hybrid plants is proposed here with a case study. It is concluded that the RES based power generation can play a vital role for green and clean energy production.

Keywords: Energy storage, environment, pollutants emission, renewable energy, renewable penetration

INTRODUCTION

The earth's atmosphere is being overloaded with Greenhouse Gases (GHG), which may create large-scale disorders in climate with severe consequences. Burning of fossil fuels accounts for major part of the GHG emissions. At present fossil fuels like coal, oil and natural gas supply approximately 86% of global primary energy needs and major share of world electricity production is this fuel based thermal plants (Akorede *et al*., 2010). The emissions from such plants cause global warming, acid rain, urban smog and hence are resulting in severe damage to the environment. It is anticipated that the failure to reduce pollutants emission from burning fossil fuels will result in an increase in the average global temperature in the range of 1.4 to 5.8°C during 1990 to 2100 period (Saidur *et al*., 2011).

Fossil fuel based power plants account for more than 66% of global electricity production and about 40% of this production is contributed by the coal fired thermal power plants alone (Jamel *et al*., 2013; Pazheri *et al*., 2012). The main pollutants from fossil fuel based plants are CO_2, SO_2, NO_X and particulate matter (PH_{10}), etc. The air pollution particles with size between 2.5 to 10 μm are called PH_{10} and include smoke, dirt, dust, mold and pollen, etc. Due to the effect of pollutants from the fossil fuel based plants, about 0.3 million people die annually worldwide and pollutants from coal fired plants alone kill about 170000 people every year (Polya, 2008). A research by Fraunhofer institute states that about 117 \$/MWh is being currently paid by European citizens for health and environmental damages caused by the generation of electricity using the conventional thermal power plants (Nathan, 2012). It is projected that power stations will contribute the major share of GHG emissions for the next 100 years (Akorede *et al*., 2010) as shown in Fig. 1. Thus, awareness on climate changes is forcing the policy of

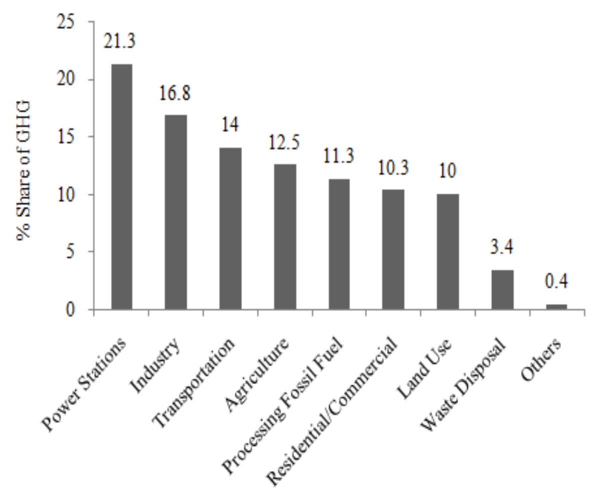

Fig. 1: The annual global projection of GHG emissions for the next 100 years from various economic sectors

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accelerated utilization of renewable energy sources for electricity production.

Electricity production using renewable energy resources reduces environmental impacts of GHG and produces least amount of secondary wastes. Natural resources like solar energy, wind power, hydropower, biomass energy and geothermal energy are the major RES for clean and green energy production. According to Green Budget Germany (GBG) research, the power generation from conventional plants is more expensive than the generation from the RES based plants if the cost paid for health and environmental damages is also considered (Nathan, 2012). RES supplied approximately 16.6% of total world energy consumption in 2010. This energy consumption increased by 22% between 2000 and 2010. Furthermore, it is estimated to increase by more than 42% during the 2010-2020 periods (Jamel *et al*., 2013; Panwar *et al*., 2011). Thus more use of RES based energy is expected to continue, which should be good news for environment.

In order to ensure high penetration of RES to grids, it is required to use energy storage facilities. Energy storage facilities can ensure clean, secure and continues supply of energy from more distributed and intermittent renewable resources. The current global storage capacities have exceeded 127.9 GW. Pumped Hydro Storage (PHS) is the fundamental storage method which alone accounts for 95% of these storage capacities (IRENA, 2012; SETIS, 2011). Deep cycle batteries with capacity ranging from 17-40 MWh and efficiency of 70-80% are commonly used in power system applications. Golden Valley Electrical Association (GVEA) in Alaska installed a battery energy supply system with nickel cadmium batteries that supplies more than 40 MW for 15 min (DeVries *et al*., 2004; Divya and Østergaard, 2009). Super capacitors represent another high power density electrochemical energy storage system while Super conducting Magnetic Energy Storage (SMES) enables energy storage in magnetic field at very low temperatures. SMES devices with capacity of 1-10 MW and efficiency of 98% are commercially available (Hall and Bain, 2008; Ibrahim *et al*., 2008). Energy is also stored in Compressed Air Energy Storage (CAES) systems by high pressure compressed air storage. The batteries of electric drive vehicles have also been recognized as means for renewable energy storage. Other types of energy storage systems including flywheel storage, thermal storage and natural gas storage, etc., are also widely used in power system applications.

Production and storage of renewable energy at times when there would be a surplus of its availability or at off-peak load hours and the reuse of such stored energy during its unavailable periods helps to increase the effective renewable energy penetration level to the grid. High potential renewable area could utilize storage facilities to harvest and utilize maximum green energy. In 2007, 20% of total electricity demand of Denmark was met by wind power alone and was targeted to increase the penetration level to 50% by 2025 by installing more efficient energy storage facilities (Divya and Østergaard, 2009). Due to the rapid growth of the renewable energy and energy storage technologies, the utilization of RES based electricity generation is increasing in all parts of the world.

The main objectives of this study are to analyze various pollutants emissions due to the generation of electricity from fossil fuels and to calculate the reduction of these pollutants due to the presence of renewable power. The amount of reduction of these pollutants with the utilization of RES and their environmental benefits are discussed here. The analysis is carried out using MATLAB simulations.

METHODS OF ANALYSIS

If W_f is the weight of fuel fired per hour in tonnes (ton) and Cv_f is the calorific value of fuel. Then the boiler input power in MW due to the burning of fossil fuel is expressed as:

$$P_{IB} = \frac{W_f . C_{vf}}{3600} \quad (1)$$

The calorific value of fuel is expressed in kJ/kg and given as follows (Mesroghli *et al*., 2009):

$$C_{vf} = 327.8C_f + 1419H_f - 137.9O_f + 92.6S_f + 637 \quad (2)$$

Here, C_f, H_f, O_f and S_f represent the percentage weight of the carbon, hydrogen, oxygen and sulphur in the fuel and can be calculated by the ultimate analysis of fuel used (Stull, 2003).

The power output of the generator P_G in MW is expressed as:

$$P_G = \eta_p P_{IB} \quad (3)$$

where, η_p is the overall efficiency of power plant which includes the efficiency of the boiler, the turbine as well as the generator, etc.

The power generated by the renewable energy resources P_R is generally variable. Hence it is considerd as a variable negetive load. Therefore P_R is deduced from the power demand P_D. In a system, P_D is generally varying with time and depends on the weather and many other factors. To ensure power balance, the total power generation P_G must equal the total demand plus the transmission line loss P_L. Hence:

$$P_G = P_D + P_L - P_R \quad (4)$$

$$P_R = xP_D \quad (5)$$

Table 1: Ultimate analysis of coal on % weight basis (Stull, 2003)

Element	Ash	Carbon	Nitrogen	Hydrogen	Oxygen	Sulphur
Weight %	41.19	31.20	0.35	4.53	22.08	0.65

Table 2: Emission coefficients of pollutants

	Poll.	α	β	γ	δ
Case A	CO_2	2.27×10^{-7}	-5.06×10^{-4}	1.1500	15.000
	SO_2	1.12×10^{-9}	-1.99×10^{-6}	0.0066	0.500
	NO_x	7.00×10^{-10}	-1.38×10^{-6}	0.0040	0.200
	PH_{10}	0.0000	-1.33×10^{-7}	0.0003	0.005
Case B	CO_2	1.84×10^{-7}	-4.13×10^{-4}	0.9270	10.000
	SO_2	1.36×10^{-9}	-3.11×10^{-6}	0.0068	0.030
	NO_x	7.47×10^{-10}	-1.72×10^{-7}	0.0037	0.010
	PH_{10}	0.0000	-1.19×10^{-7}	0.0003	0.001

where, x is the renewable energy penetration level (the ratio of renewable energy extracted to the total load demand):

$$P_L = B_{11}P_G^2 + B_1P_G + B_0 \tag{6}$$

The amounts of pollutants produced by the burning of fossil fuel at power plants depend upon the weight of fuel used, emission factor and boiler efficiency, etc. A generalized expression for the amount of pollutant 'i' emitted in ton/h is written as follow (ISCC, 2011; NPI, 1999):

$$E_{fi} = W_f e_{f_i}\left(1-\eta_{ci}/100\right) \tag{7}$$

$$i = \begin{cases} c \ \text{for } CO_2 \\ s \ \text{for } SO_2 \\ n \ \text{for } NO_x \\ p \ \text{for } PH_{10} \end{cases}$$

where, E_{fi}, e_{fi} and η_{ci} are the amount of emission, emission factor and emission control efficency for pollutant 'i', respectively. With the help of suitable curve fitting method, a generalized equation for the total pollutants emitted from a thermal power palnts can be derived using the Eq. (7) (Pazheri *et al*., 2002; TSI, 2004). Thus, the total pollutants emissions can be expressed as:

$$E_t = \sum_{i=c,s,n,p}\left(\alpha_i P_G^3 + \beta_i P_G^2 + \gamma_i P_G + \delta_i\right) \tag{8}$$

where α_i, β_i, γ_i and δ_i are the emission coefficients. After substituting Eq. (4) and (5) in (8) and simplifying, Eq. (8) can be rewritten as:

$$E_t = \sum_{i=c,s,n,p}\left(\alpha_i((1-x)P_D + P_L)^3 + \beta_i((1-x)P_D + P_L)^2 + \gamma_i((1-x)P_D + P_L) + \delta_i\right) \tag{9}$$

The amounts of various pollutants emitted from the thermal power plant and the variations of these pollutants with respect to renewable penetration level are analyzed using MATLAB simulations.

RESULTS AND DISCUSSION

We consider a hybrid system which includes coal and RES based plants for a case study in order to gain insight in planning a strategy for operating such plants. The ultimate analysis results of coal used is given in Table 1. The high calorific value of coal is calculated as 14308 kJ/kg using Eq. (2) and the efficiency of coal fired power plant are assumed as 40%. The values of B_{11}, B_1 and B_{00} are taken as 1.35×10^{-5}, -0.00016 and 0.55, respectively. The values of emission factor in kg/tonnes of coal for CO_2, SO_2, NO_x and PH_{10} are considered as 1369, 9.75, 5.3 and 0.37, respectively (NPI, 1999). Table 2 gives the emission coefficients calculated using curve fitting method. The plots of pollution emission using a polynomial of 3rd order by curve fitting method for Case A are shown in Fig. 2.

Two case studies are considered here: Case A is with uncontrolled emission and Case B is with controlled emission conditions. In Case B, each pollutant is assumed to be controlled by 20% with the aid of pollution control devices (EPA, 2000). The case studies are further divided into two sub-cases so that:

- x = 10%
- x = 30%

Table 3: Pollutants emissions (ton/h) in case A

PD (MW)	50	100	150	200	250	300	350	400	450	500
X = 0%										
CO_2	71.8970	125.8700	177.7200	227.1000	275.6900	322.1500	367.1300	410.8200	453.3900	495
SO_2	0.8289	1.1454	1.4540	1.7556	2.0510	2.3409	2.6263	2.9079	3.1867	3.4635
NO_x	0.3989	0.5894	0.7743	0.9541	1.1293	1.3005	1.4680	1.6325	1.7946	1.9546
PH_{10}	0.0198	0.0339	0.0472	0.0599	0.0720	0.0834	0.0942	0.1042	0.1136	0.1224
X = 10%										
CO_2	66.3830	115.2800	162.4400	207.9800	252.0100	294.6700	336.0600	376.3200	415.5700	453.9200
SO_2	0.7968	1.0829	1.3626	1.6364	1.9050	2.1689	2.4287	2.6852	2.9388	3.1902
NO_x	0.3795	0.5519	0.7196	0.8831	1.0428	1.1990	1.3521	1.5025	1.6505	1.7966
PH_{10}	0.0184	0.0311	0.0433	0.0550	0.0661	0.0767	0.0868	0.0963	0.1053	0.1138
X = 30%										
CO_2	55.2820	93.8220	131.3100	167.7900	203.3100	237.9500	271.7400	304.7400	337.0200	368.6200
SO_2	0.7323	0.9569	1.1775	1.3945	1.6082	1.8188	2.0265	2.2318	2.4348	2.6358
NO_x	0.3406	0.4760	0.6087	0.7387	0.8663	0.9917	1.1149	1.2361	1.3557	1.4736
PH_{10}	0.0155	0.0255	0.0353	0.0447	0.0538	0.0626	0.0710	0.0792	0.0870	0.0945

Table 4: Pollutants emissions (ton/h) in case B

PD (MW)	50	100	150	200	250	300	350	400	450	500
X = 0%										
CO_2	55.8510	99.3220	141.0600	181.1800	219.8300	257.1500	293.2600	328.3100	362.4300	395.7500
SO_2	0.3661	0.6844	0.9896	1.2825	1.5643	1.8359	2.0983	2.3526	2.5996	2.8406
NO_x	0.1968	0.3815	0.5667	0.7530	0.9410	1.1312	1.3242	1.5207	1.7211	1.9261
PH_{10}	0.0159	0.0300	0.0435	0.0565	0.0689	0.0807	0.0919	0.1025	0.1125	0.1219
X = 10%										
CO_2	51.4080	90.7920	128.7600	165.4000	200.8000	235.0800	268.3200	300.6300	332.1100	362.8500
SO_2	0.3336	0.6220	0.8997	1.1673	1.4256	1.6753	1.9172	2.1519	2.3801	2.6027
NO_x	0.1783	0.3446	0.5113	0.6787	0.8474	1.0176	1.1900	1.3648	1.5425	1.7236
PH_{10}	0.0144	0.0272	0.0396	0.0514	0.0628	0.0737	0.0842	0.0941	0.1036	0.1126
X = 30%										
CO_2	42.4640	73.5130	103.7000	133.0600	161.6500	189.5000	216.6600	243.1700	269.0900	294.4600
SO_2	0.2680	0.4955	0.7164	0.9311	1.1399	1.3432	1.5412	1.7342	1.9227	2.1070
NO_x	0.1414	0.2709	0.4005	0.5306	0.6613	0.7927	0.9252	1.0589	1.1940	1.3308
PH_{10}	0.0115	0.0216	0.0314	0.0409	0.0502	0.0592	0.0679	0.0763	0.0844	0.0923

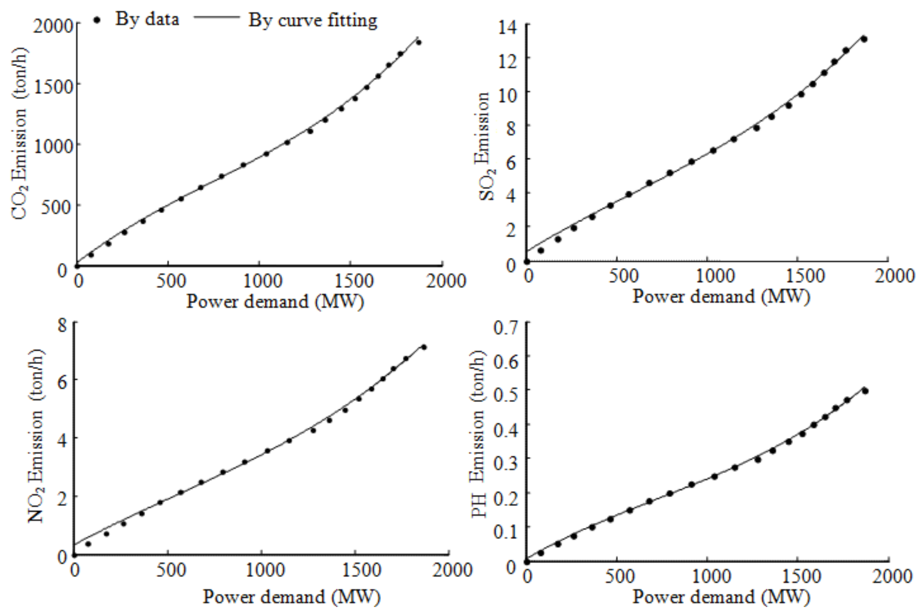

Fig. 2: Plot of pollutants emissions as a 3rd order polynomial against demand

Let E^k_{tx} and E^k_t be the amounts of total emissions with renewable power at penetration level x and without renewable power, respectively. Similarly, E^k_{itx} and E^k_{it} be the amounts of pollutant i with and without the renewable power, respectively. Here k is equal to a or b for Case A or Case B, respectively.

The amounts of various pollutants emitted with the generation of required power demand for Case A and Case B are given in Table 3 and 4, respectively. The results show that the amount of each pollutant emitted at a specified power demand is higher in Case A than the corresponding value for Case B. Compared to the other pollutant, the emission of CO_2 pollutant is significantly higher while PH_{10} pollutants is almost negligible. The amount of CO_2 emission accounts for almost 99% of the total pollutant emitted at a specific demand. At a demand of 300 MW and with 30% renewable penetration level, the emissions of CO_2 and PH_{10} pollutants in Case A are almost 238 and 0.063 ton/h, respectively, while the corresponding amounts in Case B are almost 190 and 0.059 ton/h, respectively.

The variation of the amount of overall pollutants with power demand for Case A is shown in Fig. 3 and that for Case B is shown in Fig. 4. A significant reduction in the total amounts of pollutants emission in both cases is achieved by utilizing renewable power along with conventional power. While generating a power of 200 MW by coal fired power plant, the amounts of total pollutants emitted are more than 127 and 100 ton/h for Case A and Case B, respectively. However, if 30% of this demand is met by RES based plants, then these amounts are decreased to almost 95 and 74 ton/h, respectively.

The variation of total pollutants emission with daily load demand variation is given in Table 5. The supply of peak demand of 247 MW in the presence of 20% of emission control and renewable power with 30% penetration level emits only 162 tonnes pollutants

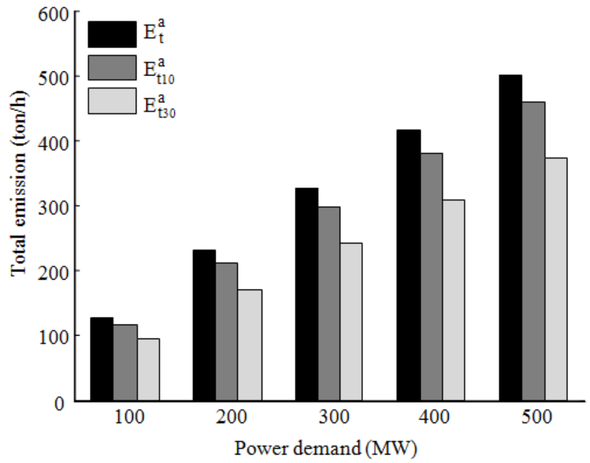

Fig. 3: Case A: variation of total amount of emission with power demand

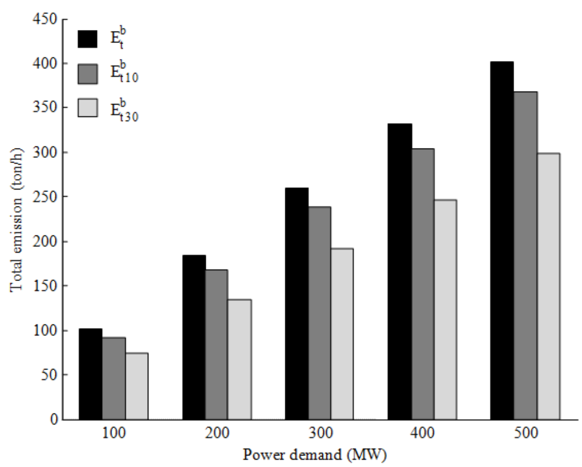

Fig. 4: Case B: variation of total amount of emission with power demand

per hour and this amount is less than the amount of pollutants emitted while generating a demand of 150 MW in the absence of emission control devices and renewable power usage. A hybrid power plant which

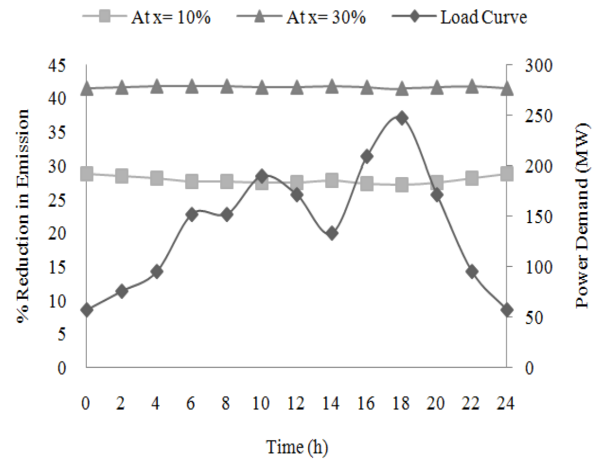

Fig. 5: Percentage reduction in pollutants emission with daily load curve

produces power by utilizing conventional and renewable energy can reduce the amount of pollutants emission in a significant manner. The presence of emission control devices and energy storage devices increases the potential of clean power production in such plants. More than 25% pollutants can be reduced if renewable power at 10% penetration is used with controlling emission by 20% as shown in Fig. 5. Moreover, it is clear from Fig. 5 that this percentage reduction in pollutants emission increases by more than 40% upon increasing the renewable penetration level to 30%. In general, as expected, the amount of pollutants emission will increase with increase in power demand and will decrease with increase in the renewable power penetration level as shown by these results. The share of renewable power impacts a considerable reduction in the pollutants emissions from power plants and therefore decreases the undesirable environmental effects and damages. Thus, a significant amount of cost paid by the citizens for the health related issues can be decreased by using renewable energy resources.

Table 5: Overall pollutants emission with daily load demand

Daily demand		Total emission (ton/h)					
		Case A			Case B		
Time (h)	PD (MW)	E_t^a	E_{t10}^a	E_{t30}^a	E_t^b	E_{t10}^b	E_{t30}^b
0	57	80.91	74.60	61.88	62.70	57.60	47.34
2	76	101.76	93.47	76.74	79.53	72.84	59.33
4	95	122.29	112.09	91.44	96.10	87.87	71.20
6	152	182.05	166.43	134.62	144.31	131.71	106.05
8	152	182.05	166.43	134.62	144.31	131.71	106.05
10	190	220.45	201.48	162.67	175.27	159.98	128.68
12	171	201.39	184.07	148.72	159.90	145.94	117.42
14	133	162.43	148.56	120.38	128.48	117.30	94.55
16	209	239.25	218.66	176.49	190.42	173.83	139.83
18	247	276.08	252.40	203.72	220.10	201.02	161.78
20	171	201.39	184.07	148.72	159.90	145.94	117.42
22	95	122.29	112.09	91.44	96.10	87.87	71.20
24	57	80.91	74.60	61.88	62.70	57.60	47.34

CONCLUSION

A case study of environmental benefits achieved by using an increased renewable penetration level is carried out using MATLAB simulations. A generalized model to calculate pollutants emission in the presence of renewable power is discussed in this study. The reductions in the amount of various pollutants emitted from the power plants at different levels of renewable power penetration levels are presented and discussed. The decrease in the amount of pollutants reduces the environmental damages and health concerns caused by the environmental pollution. The cost paid for health care and the environmental damages are also decreased with high renewable penetration is also decreased. Thus although, on the surface RES power may appear costly, its overall costs are less than the corresponding costs associated with the conventional power plants.

ACKNOWLEDGMENT

The authors would like to acknowledge Research Center and Saudi Aramco Chair in Electrical Power, College of Engineering, King Saud University for supporting this study. The support from Universiti Teknologi Malaysia under grant 002G20 is gratefully acknowledged.

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