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Comparative Analysis of AC and DC Distribution System with Respect to Harmonic Distortion Considering Daily Load Profile

Faisal Shahzad[1], Haroon Farooq[2], Waqas Ali[2], Hassan Erteza Gillani[1], Naeem Abas Kalair[3], and Mohamed Emad Farrag[4]

[1] Dept. of Electrical Engineering (Faisalabad Campus), University of Engineering and Technology Lahore, Pakistan
[2] Dept. of Electrical Engineering (RCET Campus), University of Engineering and Technology Lahore, Pakistan
[3] Dept. of Electrical Engineering, University of Gujrat, Pakistan
[4] School of Computing, Engineering and Built Environment, Glasgow Caledonian University, UK

Corresponding author: Waqas Ali (e-mail: waqas.ali@uet.edu.pk).

***Abstract* — Electrical energy is the most efficient and the cleanest form of energy at the moment that is being transmitted and distributed amongst end-users. From its earlier days, the AC system was preferred as an economical solution for transmission and distribution. However, the development in the power electronics technology and the evolution of highly efficient power electronic converters has established the resurgence of DC power system. Furthermore, the trend is shifting towards DC loads as various energy efficient appliances, such as DC inverter air conditioners, operate on DC nowadays. This further advocates the shift towards the DC power system. This research works is an effort to perform the comparative analysis of AC Distribution System (ACDS) and DC Distribution System (DCDS), with regards to power quality and harmonic distortion in particular. The comparison is performed considering load profile and load variation on daily basis. Simulations are performed in MATLAB. It has been concluded at the end that ACDS is better than DCDS in terms of power quality as total harmonic distortion of the DCDS under the same loading and same load variation during the whole day was significantly higher than that of ACDS.**

***Index Terms* — AC, DC, distribution system, power electronic converters, harmonic distortion, power quality, load profile.**

I. INTRODUCTION

Electricity is controllable, convenient, and most used form of energy and is a prime necessity to modern civilization. Its birth witnessed the war of currents between AC and DC as the medium of power transfer [1]. DC lost the battle because it did not possess the ability of voltage transformation [2]. Since that time, it became a common practice to generate, transmit and distribute electricity as AC, not only in US but all around the world [3]. Since the 1900s, much of the AC electricity is being produced using conventional sources of energy e.g. coal, natural gas, and mineral oils. With the tremendously increasing global human population the demand of electricity is climbing as well [4]. In order to meet this inflation in electricity demand, an exponential increase in fossil fuel consumption has been recorded [5]. This is an alarming situation for whole world because it not only depleting the fossil fuel reserves of planet rapidly but also posing threat to human life causing an intense increase in global warming, urban air pollution and deforestation which in turn is responsible for global rise in carbon dioxide emissions [6].

In order to avoid the fatal consequences of the climate change due to fossil fuel consumption, efforts are being made globally to utilize the renewable energy sources specifically solar PV and wind to generate electricity with zero or very little pollution to meet the increment in electricity demand [7]. However, most of the electricity generated through these renewable energy sources is DC in nature and current practice is to inject this electricity in the national grid using power electronic inverters, in the form of AC [8]. No doubt, power injection to national grid through Distributed Generation (DG) deploying renewable energy resources has innumerable benefits in terms of enhanced reliability, reduced rates of electricity and reduction in carbon dioxide emissions [9]. However, it could have some negative impacts on the performance of grid as well [10]. The power being obtained from DG is intermittent in nature and is associated with some notable amount of harmonic content which not only contaminates the power quality of existing AC system but could also change the source impedance of the network, leading to false tripping, loss of coordination, undesirable network islanding, protection blinding and unsynchronized reclosing resulting in reduced power system reliability [11].

Nowadays with the advancement in the field of power electronics, it has become a proven fact that HVDC transmission is more stable, secure, and cost effective with low transmission losses as compared to HVAC transmission especially over long distances [12]. Even on low voltage distribution side DC is striving to comeback with full swing. Until now it has been observed mostly inside devices e.g. fluorescent tubes are replaced by LED bulbs, bulky PC's are replaced by laptops, simple split air conditioning units are being replaced by DC inverter air conditioning units and above all rapidly growing electric vehicle industry, intended to replace petrol pumps with DC charging stations [2]. So, in our current AC distribution system when AC reaches at the input terminals of these loads, it is mostly stepped down and then rectified which results in substantial power loss. Thus, to eliminate these AC-DC and DC-AC conversions and also to overcome the challenges faced by the current AC distribution systems due to DG, the transformation of existing distribution grid from AC to DC is considered to be the need of time. To optimize the feasibility of this transformation approach, a comparison has been made in this paper between AC Distribution System (ACDS) and DC Distribution System (DCDS) based on harmonic distortion considering daily load profile. For this purpose, AC as well as DC distribution networks are modeled in MATLAB/Simulink. The load in each network is categorized as AC, DC and Independent load. Each network is subjected to a common load profile for a whole day and results obtained are compared on the basis of Total Harmonic Distortion (THD).

II. LITERATURE SURVEY

Due to advent of power electronic based converters, various research efforts in the past have been made to explore the practicability and viability of DC power distribution. The feasibility of a DC network at commercial level is presented in [13]. Voltage drop and power loss calculations were analysed for AC and DC distribution systems. Backup supply and protection of low voltage system were also considered. In DC, voltage levels (326V, 230V, 120V and 48V) were adopted. Authors concluded that DC system may lead to advantages if voltage level of 326V is chosen. The feasibility of a mini residential DC distribution system is presented in [14]. The authors presented that DC distribution of electric power is the efficient way of power delivery because of zero reactive power. In [8] AC and DC distribution systems for distributed generation are compared. Efficiency values for AC and DC distribution systems were obtained as 85.3% and 87.8% respectively. It is concluded that DC system can be a preferred choice as far as efficiency is concerned. In [10], construction cost and transmission loss rate at the proposed voltage levels of 10kV AC, 7.5kV DC, and 15kV DC were analyzed. The results of this work revealed that maximum transmission capacity of DC distribution system is significantly better than AC distribution and increases further with the increase in voltage level. However, DCDS is comparatively costly considering the cost of main devices i.e. DC breaker, DC converter etc. Further, it is also concluded that higher the DC load ratio, lower will be the cost and transmission loss rate of DC distribution system. In [11], an efficiency comparison of AC and DC residential distribution systems is presented. It is concluded that connection of DC loads such as LED lamps; PV panels and regenerative elevator to the DC bus are more efficient than actual AC plugs by means of rectifiers. Simulations resulted that DC distribution is more efficient than AC distribution. In [12], after comparing the two distribution networks under the same voltage levels and load technology, authors proposed that only efficiency alone cannot be the variable deciding the adoption of DCDS in comparison to ACDS.

DCDS has many advantages over ACDS in terms of integration of distributed generations. However, integration of distributed generations in AC System is more complex and requires synchronization, phase control and frequency control. But DCDS presents challenges related to the stability of the system due to inclusion of non-linear power electronic converters [15]. Harmonic distortion caused by these power converters affects the quality of the power. Though, many studies reported in literature, have investigated the power quality of DCDS [16-21] but they lack the comparison with ACDS and do not give consideration to daily load profile. So, this study is an addition to the previous works that compares the AC and DC systems at distribution level particularly accounting the power quality issues associated with these types of systems considering daily load profile and load variation.

III. SCHEMATIC OF DC AND AC DISTRIBUTION SYSTEMS

Owing to the benefits of a DC system, some topologies for DCDS have been proposed by researchers [15]. The integration of multiple sources in DC system avoids the need of phase synchronization and frequency control. However, stability challenges in DC system should be taken into account and DC system should be able to detect and clear fault on the DC bus. Due to advantage of lack of synchronization with generator, the following DCDS topology of Fig. 1 is used for comparison with the counterpart ACDS.

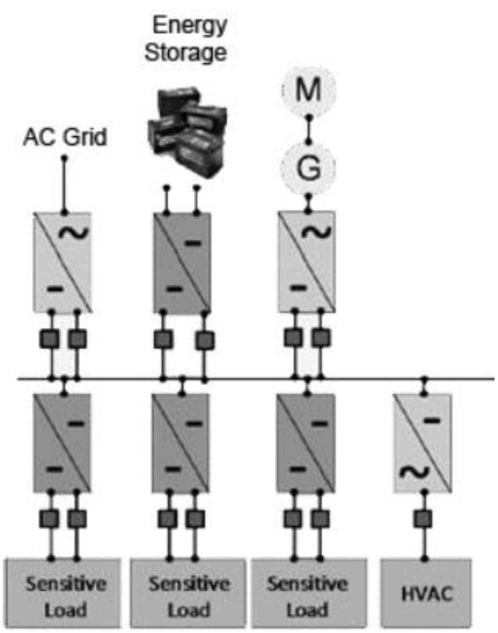

FIGURE 1. Schematic diagram of DC distribution system.

A conventional AC Distribution system with all of the components shown in Fig. 2 is used for power quality comparison.

IV. MODELING OF DC AND AC DISTRIBUTION SYSTEMS

Both cases have been provided with the same loads. ACDS consists of a 3-Phase 200kVA distribution transformer which steps down the voltage from 11kV to 230V for domestic usage, while DCDS also consists of 3-Phase transformer which also steps down voltage to be rectified.

The authoritative Energy Data Book [20] is revered for justified loading conditions which lead to a fair comparison basis for both ACDS and DCDS. Three primary areas categorized for loads are as follows.

- AC in nature (A): loads powered in ACDS by 230V but in DCDS, inverter is used.
- DC in nature (D): loads powered directly by DCDS, while under ACDS powered using rectifier to get 12V DC.
- Independent loads (I): loads powered directly by any of distribution system, AC or DC, under AC they call for 230V while under DC, for 325V DC.

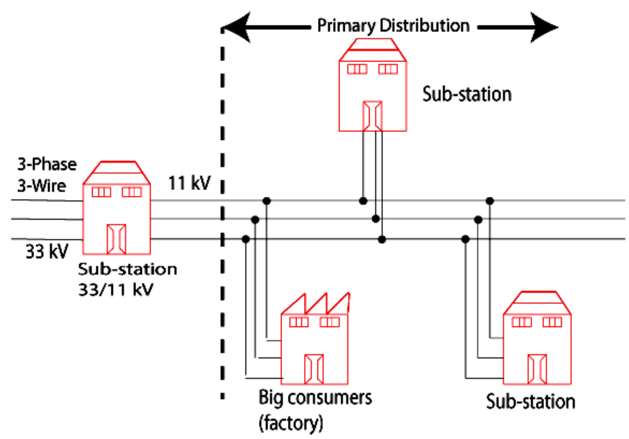

FIGURE 2. Schematic diagram of AC distribution system.

The AC load list has space cooling, refrigeration and cleaning etc. While DC loads have chip-controlled devices, the laptops, desktop computers, consoles and grid of electronics ready to soak power. While the independent loads include like space heating, cooking and water heating. The given Table I describes them in BTU.

The loads are not utilized in same manner throughout the day which calls for division of 24-hour day into three portions of day as morning (00:00 to 06:00), afternoon (06:00 to 15:00) and the night (15:00 to 00:00).

It is surmised that [21]:

- Lighting is mostly required in the evening.

- Cooking and wet cleaning is negligible during evening.
- Refrigeration is reduced during night.

TABLE I
CATEGORIZATION OF LOAD

Category	**Load categorization for distribution systems**	
	Energy used (Quad BTU)	Load Categorization
Space Heating	0.44	Independent
Water Heating	0.45	Independent
Cooking	0.18	Independent
Lighting	0.69	DC
Electronics	0.54	DC
Computers	0.2	DC
Refrigeration	0.45	AC
Wet Cleaning	0.33	AC
Space Cooling	1.08	AC
SEDs	0.42	-
Other	0.2	-
Total	4.95	-

Source: Energy Data Book [20]

Based upon these assumptions and Table I, the Table II stems out. Table II serves as backbone for the calculations performed. The per day energy demand of 30 kWh/day is taken from the doctrine of Energy Information Data [22]. This energy demand reflects the total demand of the day which requires the further division into three portions of the day in order to determine the individual energy and power demands. Thus, energy and power consumed in night, morning and afternoon is calculated using following relationships.

$$E_{x(\%)} = \frac{E_{x(\mathrm{BTU})}}{E_{t(\mathrm{BTU})}} \times 100 \quad (1)$$

$$E_{x(\mathrm{kWh})} = \frac{E_{x(\%)} \times E_{t(\mathrm{kWh})}}{100} \quad (2)$$

$$P_{x(\mathrm{kW})} = \frac{E_{x(\mathrm{kWh})}}{T_{ox(\mathrm{hours})}} \quad (3)$$

Where:

- $E_{x(\%)}$ = Percentage consumption of energy for *x* period.
- $E_{x(\mathrm{BTU})}$ = Energy consumed at *x* period in BTU.
- $E_{t(\mathrm{BTU})}$ = Total energy consumed per day in BTU.
- $E_{x(\mathrm{kWh})}$ = Energy consumed at *x* period in kWh.
- $E_{t(\mathrm{kWh})}$ = Total energy consumed per day in kWh (for this work, it is taken as 30kWh/day).
- $P_{x(\mathrm{kW})}$ = Power consumed at *x* period in kW.
- $T_{ox(\mathrm{hours})}$ = Operating time of Load at *x* period in hours.
- Index *x* represents the period of night, morning and afternoon.

For night:

$E_{night\,(\%)} = (0.56/4.95)\times100 = 11.13\%$

$E_{night(\mathrm{kWh})} = (11.13\times30)/100 = 3.394\mathrm{kWh}$

$P_{night(\mathrm{kW})} = 3.394\mathrm{kWh}/6\mathrm{hours} = 0.566\mathrm{kW}$

For morning:

$E_{morning(\%)} = (1.687/4.95)\times100 = 34.08\%$

$E_{morning(\mathrm{kWh})} = (34.08\times30)/100 = 10.22\mathrm{kWh}$

$P_{morning\,(\mathrm{kW})} = 10.22\mathrm{kWh}/9\mathrm{hours} = 1.14\mathrm{kW}$

For afternoon:

$E_{afternoon(\%)} = (2.703/4.95)\times100 = 54.79\%$

$E_{afternoon(\mathrm{kWh})} = (54.79\times30)/100 = 16.437\mathrm{kWh}$

$P_{afternoon(\mathrm{kW})} = 16.437\mathrm{kWh}/9\mathrm{hours} = 1.83\mathrm{kW}$

TABLE II
DIVISION OF LOAD

Category	**Load division into three portions of the day**		
	Night (Quad BTU)	Morning (Quad BTU)	Afternoon (Quad BTU)
Space Heating	0.098	0.122	0.220
Water Heating	0.031	0.140	0.279
Cooking	0.000	0.090	0.090
Lighting	0.048	0.178	0.464
Electronics	0.018	0.165	0.357
Computers	0.006	0.052	0.112
Refrigeration	0.031	0.209	0.209
Wet Cleaning	0.000	0.165	0.165
Space Cooling	0.240	0.300	0.540
Other	0.029	0.086	0.086
SEDs	0.060	0.180	0.180
Total	0.560	1.687	2.703

The calculated power consumption of three portions of the day i.e. night, morning and afternoon is further used to compute the power demand for AC loads, DC loads and Independent loads operating during these periods as below.

DC load demand at night:

DC Load = Lightening + Electronics + Computers + Others/3 + SEDs/3
= 0.048 + 0.018 + 0.006 + 0.029/3 + 0.06/3

$= 0.101$ Quad BTU

$\% \text{ of DC Load} = \text{DC Load}/E_{night(\text{BTU})}$

$= 0.101/0.56$

$= 18.04\%$

$\text{Power Demand (DC Load)} = (\% \text{ of DC Load} \times P_{night(\text{kW})})/100$

$= (18.04 \times 0.566)/100$

$= 0.102\text{kW}$

<u>AC load demand at night:</u>

$\text{AC Load} = \text{Space Cooling} + \text{Refrigeration} + \text{Wet Cleaning} + \text{Others}/3 + \text{SEDs}/3$

$= 0.240 + 0.031 + 0.00 + 0.029/3 + 0.06/3$

$= 0.30$ Quad BTU

$\% \text{ of AC Load} = \text{AC Load}/E_{night(\text{BTU})}$

$= 0.30/0.56$

$= 53.70\%$

$\text{Power Demand (AC Load)} = (\% \text{ of AC Load} \times P_{night(\text{kW})})/100$

$= (53.70 \times 0.566)/100$

$= 0.301\text{kW}$

<u>Independent (Ind.) load demand at night:</u>

$\% \text{ of Ind. Load} = 100 - (\% \text{ of DC Load} + \% \text{ of AC Load})$

$= 100 - (18.04 + 53.70)$

$= 28.26\%$

$\text{Power Demand (Ind. Load)} = (\% \text{ of Ind. Load} \times P_{night(\text{kW})})/100$

$= (28.26 \times 0.566)/100$

$= 0.158\text{kW}$

Correspondingly, the power demand of AC loads, DC loads and Independent loads for morning and afternoon are worked out by first taking into account the individual power consumption for morning and afternoon in conformity with Table II. The results of calculations are presented in Table III.

This desists to establish the statistics for different categories of load in accordance with Energy Data Book. Very few parameters were surmised for DCDS and ACDS clinch. MATLAB/Simulink was employed to model DCDS and ACDS.

V. SIMULATION AND RESULTS

The DCDS is smart in its topologies as it deploys the rectification of the energy sources rather than the conversion for powering the loads. The 12V buck converter provides power to DC loads while AC loads are powered by inverters adhering to IEEE standards.

TABLE III
POWER DEMAND

Category	Power demand in kW for the whole day		
	Night (kW)	Morning (kW)	Afternoon (kW)
I	0.158	0.440	0.678
A	0.301	0.763	1.003
D	0.101	0.484	1.022
Total	0.560	1.687	2.703
Percentage of total DC load	18.03%	28.69%	37.80%

For DCDS, all types of energies are rectified to form DC bus as shown in the Fig. 3. A secondary distribution system is the payload to this bus. The load is simulated by establishing a colony model consisting of 50 building blocks loaded with all categories of load combinations.

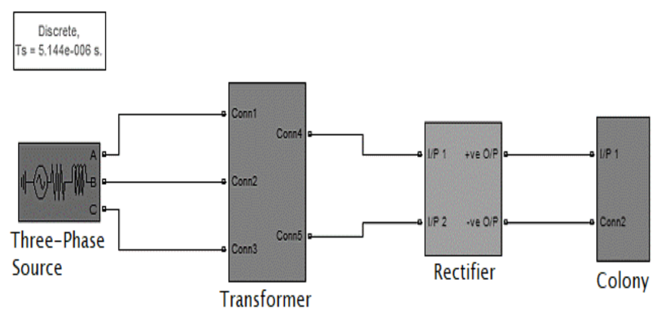

FIGURE 3. Simulink diagram of DCDS.

Delineated in Fig. 3 is one of the 50 building blocks in the colony. It hauls DC voltage as input; AC appliances are given AC using inverters while independent loads are served 325V DC as in Fig. 4.

Power demand for AC loads is not any lesser than that of DC loads. As we entail a comparison, the ACDS is portrayed in MATLAB/Simulink under the same loading conditions along with the same time phases. The ACDS comprises of a distribution transformer which steps down the power obtained from utility grid. The final model of ACDS using MATLAB/ Simulink including transformer to power the colony of 50 building blocks is shown in Fig. 5.

The comparative analysis is ready to be run as we have established attributes for both, including input and output. DCDS is expected to challenge the lead of ACDS. The AC and DC comparison is to be set by comparison of DCDS and ACDS power quality. Both distribution systems are to be tested with same loading conditions and equivalent parameters in each. power quality is elucidated as "any changes in voltage or current waveform". The IEEE standards establish in IEE-519-2014 [23-24] that Point of Common Coupling (PCC) is "Point on a public power supply system, electrically nearest to a particular load, at which other loads are, or could be connected". This definition enjoins to take all simulation results at PCC and is shown in Fig. 6 and Fig. 7.

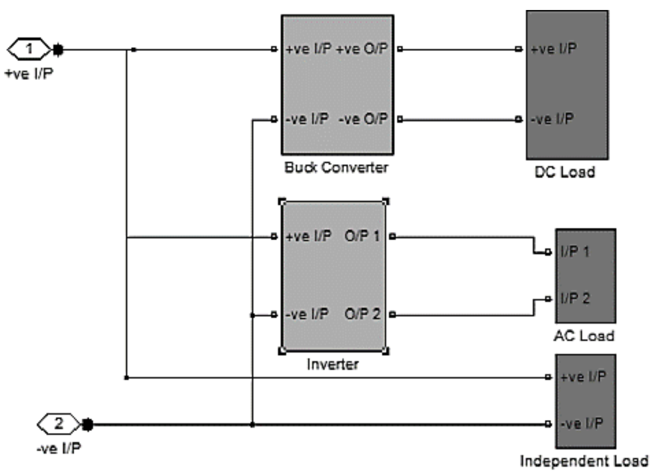

FIGURE 4. Power supply to all categories of load in DCDS.

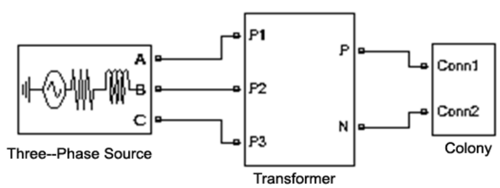

FIGURE 5. Simulink diagram of ACDS.

Harmonic analysis performed for DCDS and ACDS under same loading conditions for night, morning and afternoon are summarized in the Table IV. Total Harmonic Distortion (*THD*) can be defined as [23]:

$$(\%)THD = \frac{\sqrt{\sum_{h=2}^{\infty} M_h^2}}{M_1} \times 100 \quad (4)$$

where M_1 and M_h represent the magnitude of the fundamental and the h^{th} harmonic component, respectively, of the current or voltage waveform. According to the IEEE standard [23], Total Harmonic Distortion in Voltage (THD_v) at the PCC should not go beyond 8% for voltage level up to 1 kV.

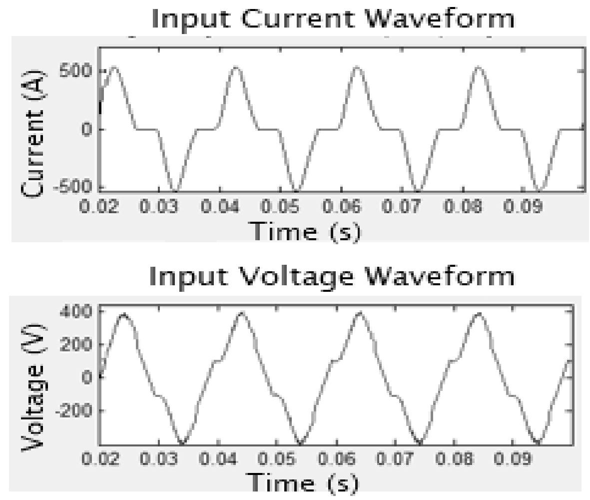

FIGURE 6. Harmonic analysis of a colony in DCDS.

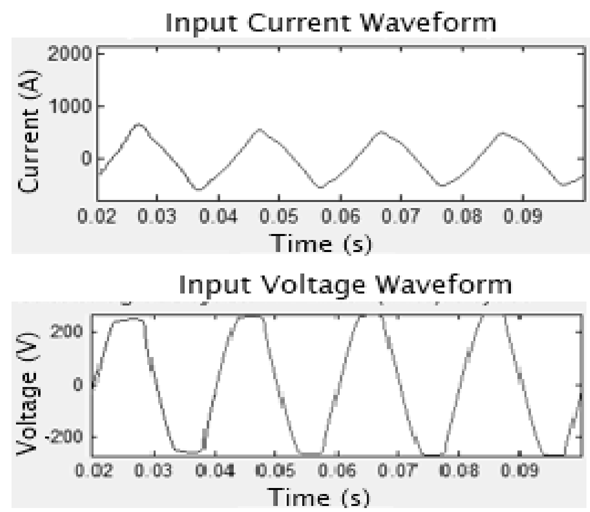

FIGURE 7. Harmonic analysis of a colony in ACDS.

TABLE IV: RESULTS

Distribution system type	**Total hormonic distortion (*THD*)**		
	Time Period	THD_i	THD_v
DCDS	Night	71.64	12.65
	Morning	58.62	19.18
	Afternoon	46.93	19.79
ACDS	Night	7.60	5.87
	Morning	14.97	3.43
	Afternoon	12.00	12.68

It is evident from the results given in Table IV that THD_v for DCDS is beyond the IEEE threshold throughout the day. However, THD_v for ACDS is within the limits throughout the day except during the afternoon because of the increased D category loads. Based upon the comparison of THD_v, ACDS is better as compared to DCDS.

IV. CONCLUSIONS

The prime focus of the research was to perform the comparative analysis of ACDS and DCDS under diversely varying loads during the whole day. The comparison was based viewed from the perspective of harmonic distortion. MATLAB/Simulink models for both systems were developed to compare the results. Power quality analysis under the same loading conditions during the whole day was performed to find a better power system. The complete day was divided into three portions i.e. night, morning and afternoon. The results showed that the THD_v of both the systems increased with the increased in the DC loads. However, THD_v of the DCDS under the same loading and same load variation during the day was significantly higher than that of ACDS. THD_v for DCDS was found beyond the acceptable IEEE limits. Therefore, it is suggested to enforce the adherence to the harmonic standards by the load manufacturers so that the transition to the DCDS could be sustainable.

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