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Research Article

Effects of Solar Photovoltaic Penetration on the Behavior of Grid-Connected Loads

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Recently, the authority for electricity regulations in Oman introduced a new regulation for grid-connected photovoltaic (PV) systems. One of the main concerns is how the penetration of the grid-connected PV systems would affect the Mazoon Electricity Company's (MZEC) load behavior, especially at peak times. This paper presents the behavior of grid-connected loads considering the MZEC, which is one of the power distribution companies in Oman. The Al Bashir primary substation load distribution network was used as a case study. The MZEC peak load pattern was considered with respect to solar PV connection regulations in Oman. Furthermore, the various timings for electricity billing and the expected incentives were also used in evaluating the economical benefits of integrating the solar PV systems into the power grid. Data were collected for two years for the feeder and distribution transformers in the power grid. The export and import average power generation within the period of the study were also investigated. The behavior of the grid loads was investigated before and after installing the PV systems. The variables of the average power, load import, and export for different periods were used to evaluate the system performance. The obtained results reflect that with proper synchronization of the solar PV systems in the power grid, the maximum load of the primary substation decreased from 80% to 40%, considerably saving cost. Consequently, more consumers could be fed with the excess solar power, with less distribution transformers in the power grid.

1. Introduction

Recently, the integration of renewable energy is on the rise, due to its numerous benefits, such as clean energy, cheaper form of electricity supply, zero carbon emissions, and eco-friendly in nature, with no harmful environmental pollution. The penetration of renewable energy resources in the power grid would encourage distributed generation, in order to manage electricity demand and generate clean on-site power. This would improve the reliability of the power system and mitigate the system losses that are bound to occur. In addition, the integration of renewable energy into the power grid would encourage the government's energy policies in any country, in view of reducing carbon emissions, and improving energy supply, thereby promoting more competitive markets [1, 2]. Amongst the various renewable energy resources, solar energy is widely used due to its abundance, especially in the Middle East, where the Gulf Corporation Countries (GCC) are located [3, 4].

The world market for solar photovoltaic (PV) systems has increased significantly [4, 5]. Recently, solar PV module prices have decreased while emerging market prices have increased [6–8]. In 2020, global cumulative solar PV capacity amounted to 773.2 Gigawatts, with 138 Gigawatts of new PV capacity installed in that same year [9, 10]. The drivers for this increase are the need to reduce gas emissions, diversify energy sources, energy efficiency, lower capital costs, and shorter construction time. With high levels of residential grid-connected solar PV and the planned utility scale solar PV units that will be connected to the grid, it becomes necessary to study the impact on the power networks. Photovoltaic generating units connected to power networks may have several impacts on the power system, such as voltage rise at the load bus, increasing the current in the conductor, and power quality issues. The voltage rise can be limited by controlling the active and reactive power injected by solar PV or by reducing the voltage level at the substations. Based on the solar PV size, grid-connected PVs can be classified into three categories: utility scale (megawatt), medium scale (100 kW to 1 MW), and small scale (up to 100 kW) [11–13].

The Amal East and West solar projects by the Petroleum Development Company of Oman [14, 15], are some of the signs that Oman is pushing forward with its renewable energy goals. These solar farm projects have very high solar power generating capacities in the region. Also, there is a 50 MW wind farm project [16] in Salalah, which is generating power on the Omani grid and at the same time creating employment opportunities in the country. Based on the literature, Oman is an attractive location for the conversion of renewable energy to power supply because of its geographical structure and coastline, with immense solar radiation outreach [17, 18]. The average solar radiation range of Oman is between 5.5 and 6 kWh/m^2 in July to 2.5–3 kWh/m^2 in January [19].

The market structures for electricity systems in Oman are: the Main Interconnected System (MIS), the rural system, and the Salalah power system [16]. The peak demand in the MIS (the main grid covering much of the northern half of Oman) is projected to rise 4 percent annually in the expected case to reach 8,371 MW in 2027 [20]. As reported in [21], the electricity demand for the MIS for the various governorates in the Sultanate would grow by 7–11%, although some shortcomings are expected in the integration of renewable energy sources [22], in order to achieve this target. The Sultanate of Oman's production of electricity increased by 7.9% by the end of September 2021 to reach 32,411.8 GWh compared to the end of September 2020, when the total production was 30,043.1 GWh [23]. [24–27] reported that the highest renewable energy penetration in Oman could be achieved with the help of solar energy.

There are institutions and policies regarding the penetration of renewable energy sources into the power grid in the GCC region. The latest version of the Grid Code in Oman contains technical requirements and criteria for connecting renewable energy systems to the power grid. In the literature, a lot of work has been done regarding large-scale solar PV and wind power plants already connected to the Oman power grid, based on the guidelines, and technical requirements for connecting renewable energy systems, as set out by the stipulated grid codes [28]. Al Riyami et al. in [29] carried out a study on the connection of a 500 MW photovoltaic power plant to the Oman grid at Ibri. In this study, a technoeconomic evaluation of a 500 MW solar power plant connected to the main interconnected and transmission system of Oman at Ibri was investigated. The reason was to ascertain the required investment on the basis of ensuring a rigid and well-structured power transmission network in Oman for effective operation. The authors proposed and compared connection strategies considering cost and performance based on the grid codes in conjunction with environmental factors. In [30], a detailed grid impact analysis of the penetration of the Dhofar wind farm in the southern part of Oman on the transmission system has been reported in the literature. The authors developed a model of the entire power system of Oman for steady-state and dynamic studies with the intention of building confidence in the integration of the first wind farm into the Oman grid, considering the planning criteria and stipulated requirements of the grid codes and the transmission security standards in Oman presented in [31]. The Doubly Fed Induction Generator (DFIG) and the technology of the asynchronous generator with a fully rated converter were used in the study. The obtained results for the load flow and stability analyses of the model system reflect that the connection of the first wind farm to the Dhofar power network would not result in any adverse effects. A further study was carried out in [32], regarding the power quality of the Dhofar 50 MW wind farm. The main factors influencing the power quality performance of the Dhofar power grid as a result of the integration of the wind farm were reported by the authors in this work. A review of fundamental aspects influencing the power quality with respect to the grid codes performance presented in [28, 31], were taken into consideration. The power quality assessment is imperative as part of the license obligation for a transmission operator and is paramount to the wind farm developers in Oman for filter design and compensation sizing. In [33], the authors expanded the study carried out in [29] to a 1700 MW Sohar-3 power station in the Oman power grid. The options for connecting the Sohar generating plant to the Main Interconnected Transmission System (MITS) were assessed, and the most efficient financially, technically, and lower-risk option was selected as the best for the effective operation of the power system.

This paper presents the effects of photovoltaic integration on the behaviour of grid-connected loads. The work considered the load behaviour of the Mazoon Electricity Company (MZEC) at peak and off-peak times, before and after the integration of solar PV into the power grid, based on the new regulation scheme for renewable energy penetration in Oman. The MZEC is primarily undertaking the regulated business of distribution and supply of electricity to some governorates in Oman under a license issued by the Authority for Electricity Regulations (AER) in Oman. The study covered the growth of the MZEC peak load demand over the years, from 2008 to 2019, and the concept of Oman regulation regarding solar PV connection to the national power grid, based on the incentive charges approved by the AER for peak and off-peak periods. The Al Bashir primary substation load was considered in the study to investigate the effect of solar PV integration on its load behavior. The variables of the average load import and export for two consecutive years were used in the evaluation of the performance of the system. The study reflected that the behavior of the loads, in the power grid under study changed after the installation of the solar PV system. Also, from the study, it could be ascertained that the best time to export power to the grid is during the day. Moreover, there is no need to invest more in distribution transformers in the power grid since there would be a possible reduction in the average load on the network with the solar PV installations. Therefore, in the near future, new consumers could be fed from the excess solar PV power in order to save cost.

2. The Mazoon Electricity Company

MZEC is a closely held Omani joint stock company registered under the commercial companies' law of Oman. The establishment and operations of the company are governed by the provisions of the law for the regulation and privatization of electricity and related water sectors (the sector law), promulgated by Royal Decree 78/2004 and subsequent amendments. The company is primarily undertaking the regulated business of distribution and supply of electricity in southern Batinah, Dakhiliyah, southern Sharqiyah, and northern Sharqiyah governorates of Oman, under a license issued by the authority for electricity regulations in Oman, as illustrated in Figure 1 [34].

The company commenced its commercial operations on the 1st of May 2005, following the implementation of a decision by the Ministry of National Economy (issued pursuant to Royal Decree 78/2004). The company is to function as a major distribution operator of the system and act as a supplier of electricity. The following are some of the major roles of the company. First and foremost, to provide financial responsibilities; operation; maintenance; development and expansion of the 33 kV, 11 kV distribution and low tension side networks, based on relevant performance security standards and safety measures. Also, the company is to contain all the demand for electricity supply in areas within its reach. Furthermore, it is expected that the company would carry out meter readings, generate electricity bills for consumers and ensure payment of such bills.

The company's distribution network consists of various voltage levels; 33 kV, 11 kV and 0.433 kV, respectively. The network consists of 33/11 kV primary substations, 11/0.433 kV distribution substations, 33/0.433 kV substations, and the cables and overhead lines at these voltage levels. MZEC has experienced an average growth of 6.4% in load annually. Figure 2 shows the trend of growth in customers from 2008 (with 990 MW) to 2019 (with 2,233 MW) for the Mazoon electrical network during the period of this study.

3. The Solar PV Model

The dynamics and mathematical model formulation of a solar PV module are clarified based on the physical model of a silicon solar cell [35]. The steady-state and dynamic performance of solar PV is imperative to understand the PV characteristics for the stability of the overall PV system. There are two main types of models in solar PV cells; the single-diode and double-diode models. These models take solar PV irradiance and temperature as input factors and create the I–V and P–V output characteristics [36]. Figure 3(a) shows the equivalent circuit of a single-diode model for PV cells. The output current depends on the characteristics of the semiconductor material used in the cell and other factors like the area of the cell, solar irradiation, and temperature. The performance of the single-diode model depends on the diode reverse saturation current (I_r), photocurrent (I_{ph}), series resistance (R_s), and shunt resistance (R_p). The series resistance is the internal loss due to current flow and affects the relationship between the P–V open-circuit voltage and maximum power. The shunt resistance is connected in parallel with the diode and determines the leakage current to the ground. Usually, the values of R_s and R_p are assumed to be zero. The output current (I) can be expressed mathematically as (1) for characterizing the I–V performance of a single-diode [36].

$$I = I_{ph} - I_r\left[\exp\left(\frac{q(V + IR_s)}{kT_{cell}}A\right) - 1\right]. \tag{1}$$

In (1), q is the electron charge constant value ($1.6\,x\,10^{-19}C$) and K ($1.38\ x\ 10^{-23}$J/K) is Boltzmann's constant current, V and I are the cell terminal voltage and current, respectively. T_{cell} is the temperature of the cell in Kelvin. The current produced mainly depends on solar radiation and cell temperature, as expressed in (2) as follows:

$$I_{ph} = \left[I_{sc}\left(T_{ref}\right) + ki\left(T_{cell} - T_{ref}\right)\right]H. \tag{2}$$

From (2), I_{sc} (T_{ref}) is the short circuit current at 25°C reference temperature and H is the solar isolation in kW/m^2. The reverse saturation current can be written as follows:

$$\begin{aligned} I_r &= I_{rs}\left(\frac{T_{\text{cell}}}{T_{\text{ref}}}\right)\left[\exp\left(qEG\frac{1/T_{\text{ref}} - 1/T_{\text{cell}}}{kA}\right)\right],\\ I_{rs} &= \frac{I_{sc}\left(T_{\text{ref}}\right)}{\left[\exp\left(q * V/kAT_{\text{ref}}\right)\right]}. \end{aligned} \tag{3}$$

The output current equation for the single-diode model could be expressed as follows [36]:

$$I = I_{ph} - I_0\left[\exp\left(\frac{V + IR_s}{aV_T}\right) - 1\right] - \left(\frac{V + IR_s}{R_P}\right), \tag{4}$$

where I_{ph} is current generated by the incidence light, I_0 is the reverse saturation current, V is the thermal voltage, $V = kT_{\text{cell}}/q$ and a is the diode ideality factor. Hence, the terminal voltage (V_{oc}) in open circuit where I = 0 is

$$V_{oc} = \left(\frac{akT_{\text{cell}}}{q}\right)\ln\left(1 + \frac{I_{sc}}{I_s}\right). \tag{5}$$

The single-diode model is considered to be a constant value and close to unity at higher voltages, while the recombination in the device is subject to the surfaces and the bulk areas. The connection recombination is modelled by adding the second diode in parallel with the first diode as shown in Figure 3(b) and setting the ideal factor characteristically to the value of two. The output current equation of the two-diode model is given as [36, 37]

$$\begin{aligned} I = {} & I_{ph} - I_{01}\left[\exp\left(\frac{V + IR_s}{a_1 V_{T1}}\right) - 1\right]\\ & - I_{02}\left[\exp\left(\frac{V + IR_s}{a_2 V_{T2}}\right) - 1\right] - \left(\frac{V + IR_s}{R_P}\right), \end{aligned} \tag{6}$$

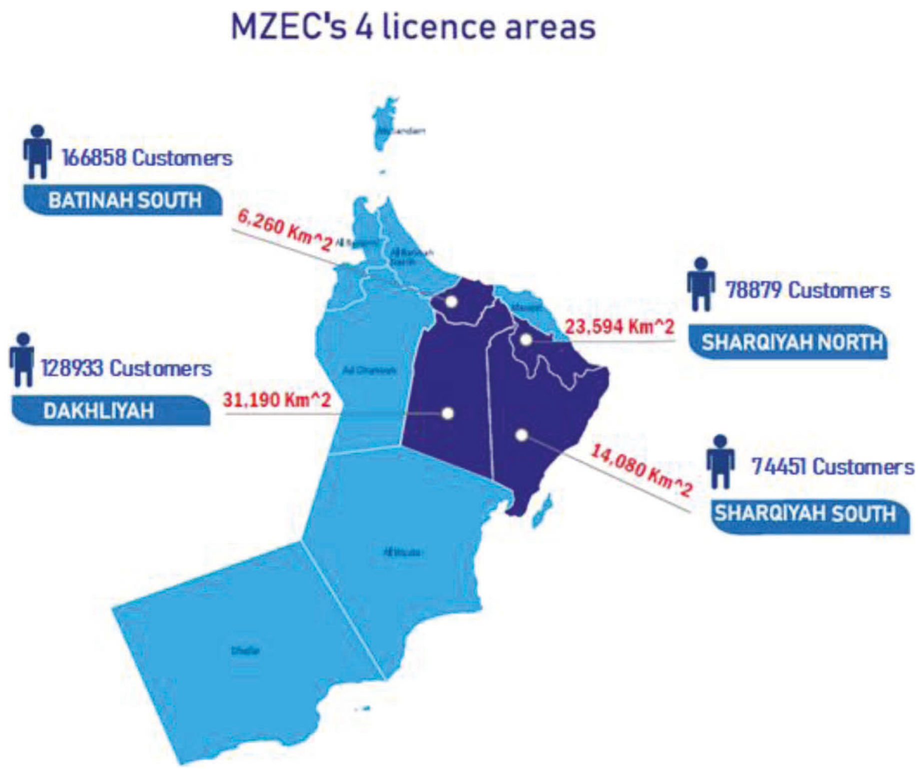

FIGURE 1: Regions covered by Mazoon Electricity Company in Oman.

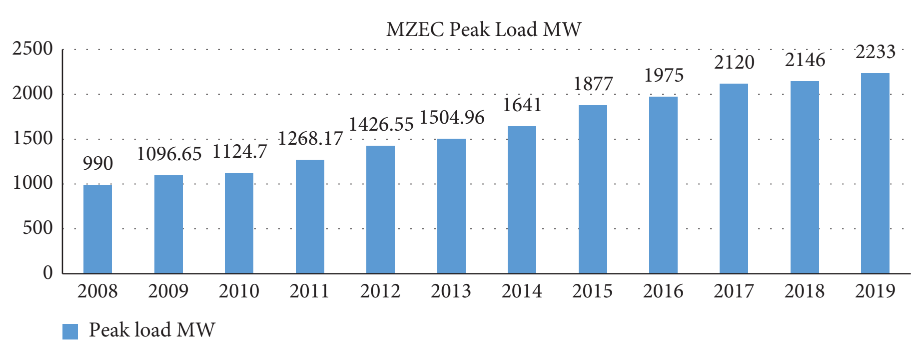

FIGURE 2: Growth in peak load for Mazoon Electricity Company.

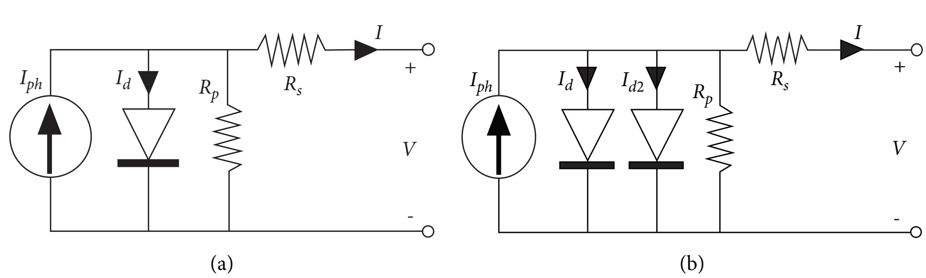

FIGURE 3: Solar PV cell model. (a) Single-diode model PV cell. (b) Double-diode model PV cell.

where I_{01} and I_{02} are the reverse saturation currents of diode 1 and 2, respectively, V_{T1} and V_{T2} are the thermal voltages of the respective diodes, a_1 and a_2 are the diode ideality constants.

4. The PV Power Conditioning Model

One of the main issues of grid-connected solar PV systems is how to achieve optimal compatibility of the solar PV arrays

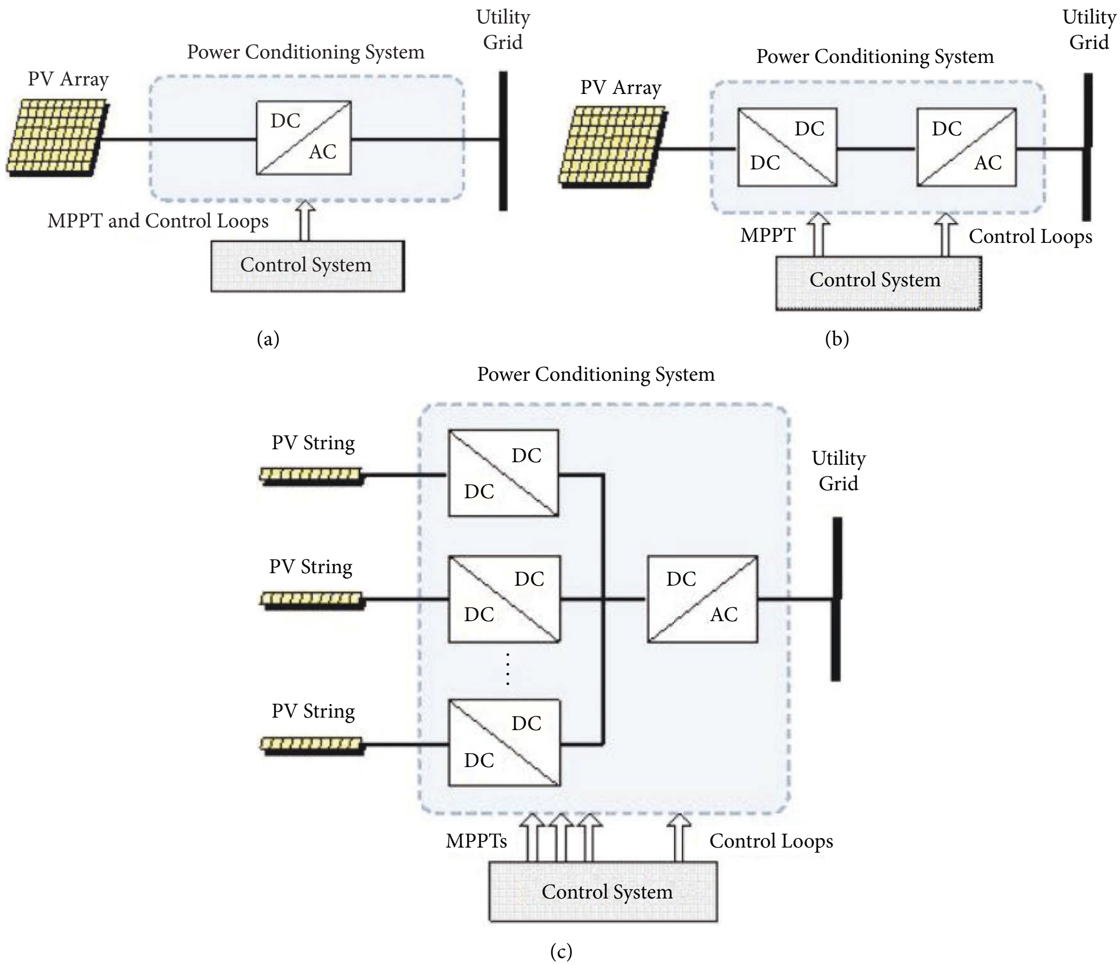

Figure 4: Solar PV power conditioning system topologies. (a) Single-stage inverter structure. (b) Dual-stage inverter structure. (c) Multi-stage inverter structure.

with the power grid. The solar PV array produces an output DC voltage having variable amplitude; thus, an extra conditioning circuit is necessary in order to achieve the amplitude and frequency requirements of the AC power grid for proper synchronization. Due to the fact that the output of solar PV panels is direct current, the solar PV power conditioning system has a DC-AC inverter for the conversion of the DC output current from the solar PV arrays into an AC synchronized sinusoidal waveform.

The procedure used for power extraction of solar radiation by the solar PV is another major concern in grid-connected PV systems. This concern is influenced by the nature of PV arrays, since the PV modules are nonlinear systems and atmospheric conditions, such ase solar radiation and temperature affect its output power. Therefore, a maximum power point tracking (MPPT) technique would help transfer the maximum solar array power that can be achieved to the power grid during operation. Consequently, grid-connected solar PV systems should carry out proper extraction of maximum output power from the PV array and dissipate sinusoidal current into the power grid.

In light of the above, the power conditioning system of a solar PV could be grouped with respect to the number of power stages as; single-stage, dual-stage, and multi-stage schemes, in Figure 4 [38]. The single-stage topology (Figure 4(a)) connects the solar PV array directly to the DC bus of the power inverter. Therefore, the MPPT of the solar PV and the inverter current and voltage control loops are done in a single-stage. A DC-DC converter known as a chopper acts like an interface between the solar PV array and the inverter in the dual-stage structure in Figure 4(b). The extra DC-DC converter between the solar PV and the inverter carries out the control of the MPPT. In the multi-stage structure in Figure 4(c), a DC-DC converter connects each string of the solar PV modules to the inverter system. Therefore, a DC-DC converter does the MPPT control of each string, while a power inverter handles the current and voltage control loops.

In recent distributed energy applications, the dual-stage solar PV power conditioning system is employed because of the high power quality, reliability, and flexibility of the solar PV system requirements. Thus, a better operation of the grid-connected PV system based on degree of freedom is obtained in the dual-stage structure than in the one-stage structure. This is because an additional DC-DC boost converter would help achieve various control objectives such

Table 1: Periods of electricity billing approved by authority of electricity regulations Oman.

	Time T1	Time T2	Time T3	Time T4
Time of the day register identification	Off-peak	Weekday-peak	Night-peak	Weekend day-peak
Time slot	02:00 to 13:00 17:00 to 22:00 16 hrs	13:00 to 17:00 4Hrs	22:00 to 02:00 4Hrs	13:00 to 17:00 4Hrs

Table 2: Incentive charge approved by authority of electricity regulations Oman.

Months	Off- peak–(Omani Baisa)	Weekday-peak–(Omani Baisa)	Night-peak–(Omani Baisa)	Weekend day-peak–(Omani Baisa)
January-March	12	12	12	12
April	14	14	14	14
May-July	17	67	26	39
August-September	15	26	21	19
October	14	14	14	14

as reactive power compensation, voltage control, and power oscillations damping. Although the case study used in this paper in Section 6 employed the single-stage configuration.

5. Concept of Oman Regulation for Grid-Connected Solar PVs

The concept of Oman regulation for solar PV connection to the national power grid is divided into two schemes; mechanical design and supply charges. The mechanical scheme entails that the support structures and arrangements for installing the solar PV units should comply with the regulations, standards, and construction requirements. Provisions must be placed in ascending order of the solar PV modules to pass them with the maximum expansion-contraction of the units at expected operating temperatures, according to the manufacturer's applicable regulations. The current mounting structures, cables, and ducts are also included in this regulation. Solar PV group support structures must comply with local standards, industry standards, and regulations with loading characteristics. The second scheme of the PV connection regulation is about supply charges. In this study, the power export cost is the total cost of the power procurement from customers, which is collected based on certain periods and priced at different rates as shown in Tables 1 and 2 respectively [34, 39]. The data were collected based on the time of the day considering four scenarios; off peak, weekday peak, night peak and weekend day peak, considering the various timings shown in Table 2. From Table 2, the highest supply charges by the electricity regulation authority happen between the months of May and July for off-peaks, weekday peaks, night peaks, and weekend day peaks. Also, from Table 2, a 100 Omani Baisa note is currently worth 26 cents (USD).

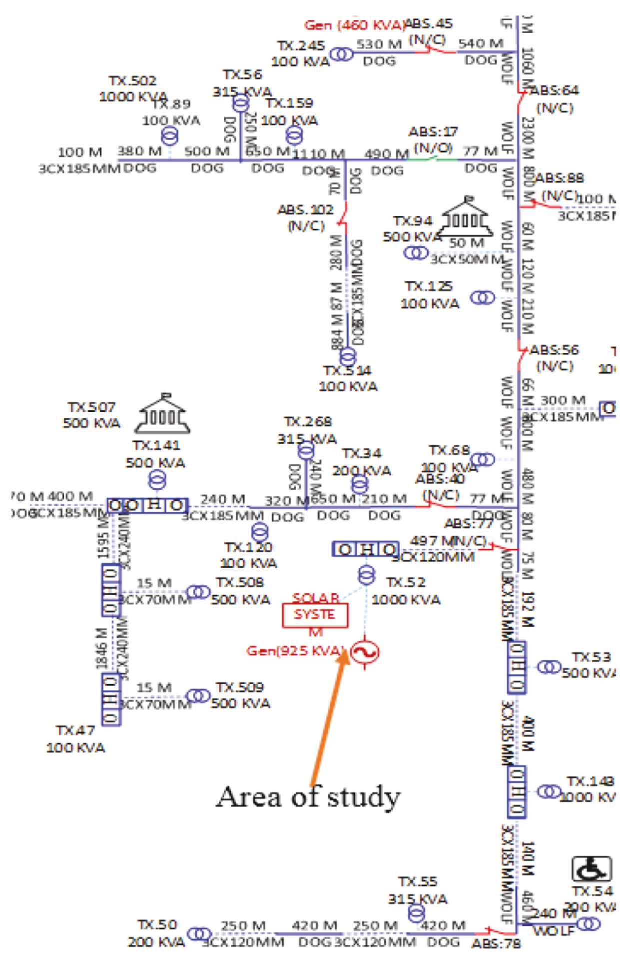

Figure 5: Al Bashir primary substation load distribution network (case study).

6. The Al Bashir Load Case Study

The number of customers installing solar PV systems based on the new regulation scheme in MZEC, in the Sultanate of Oman, is on the rise. These customers are connected to the MZEC network in different areas. In addition, the maximum capacity of the solar PV system is different for each customer, depending on the connected loads on the premises. The salient part of this study is to compare the load behavior

Table 3: Load of Al Bashir primary substation and distribution transformer-52 in 2018 and 2019.

	Al Bashir 11 kV feeder-1		Distribution transformer-52, 1000 kVA	
Month	2018—average kW	2019—average kW	2018—average kW	2019—average kW
January	950	1000	271	285
February	960	1000	274	285
March	1500	1627	428	463.6
April	1800	2200	513	627
May	2500	2391	713	384.3
June	3000	2777	852	380.8
July	3100	2655	884	427.5
August	3200	2815	912	520
September	2800	2356	798	342.2
October	2000	1605	570	168.8

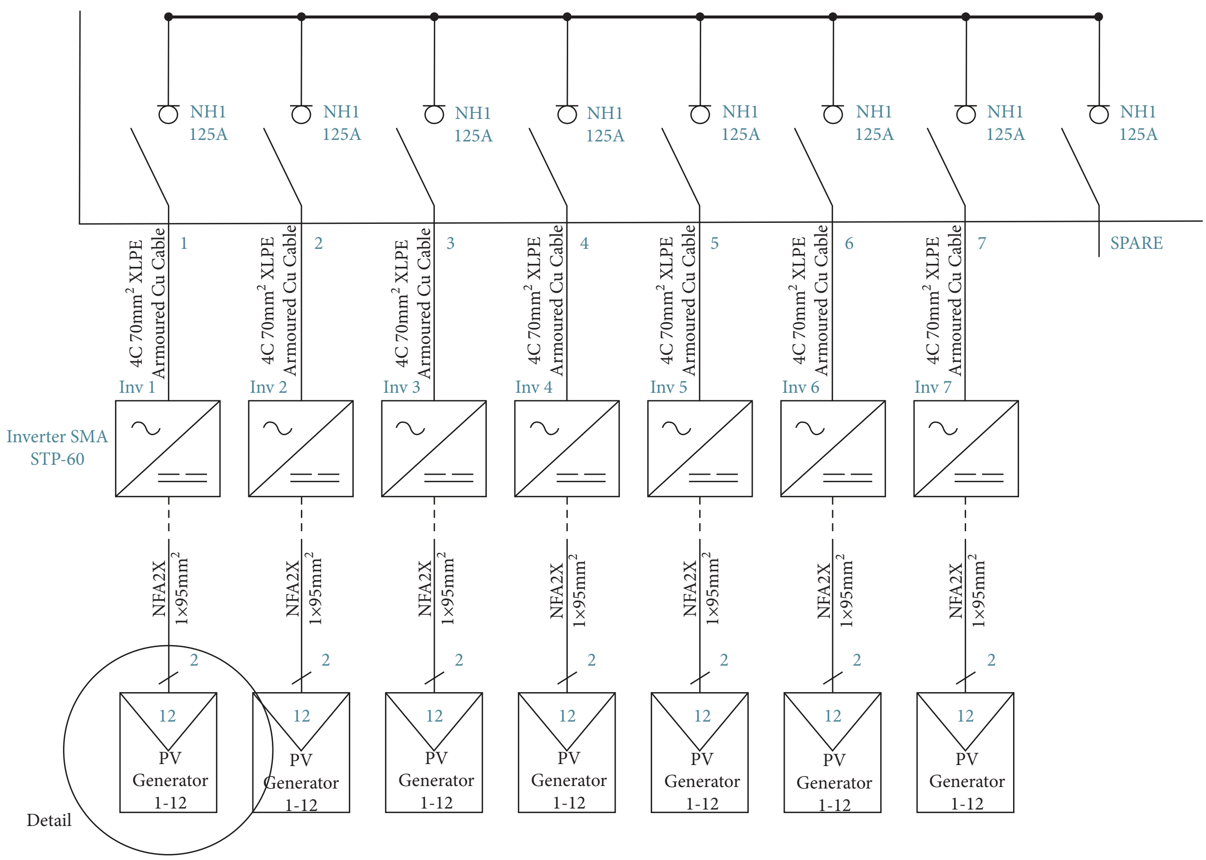

Figure 6: Single line diagram of the Al Bashir solar PV farm system connection.

of the MZEC network before and after installing a solar PV system. In this study, the Al Bashir farm load was used in investigating the behavior of the system variables before and after installing solar PV. The Al Bashir farm is located in Wilayat Adam in Al Dakhiliyah governorate and the total connected load of the premises is 740 kW. It is fed from Al Bashir primary substation by 2 × 6 MVA from feeder-1 as shown in the single line diagram of Figure 5 [39]. The silicon monocrystalline technology of solar cells is used in the solar PV plants under study because as the performance of the solar cell technology differs widely, so does power output throughout the day.

The Al Bashir primary substation is 2 × 6 MVA, and is fed from Adam's grid at 2 × 40 MVA. The expected load for this primary substation is 5.2 MVA (at 33 kV side), which is classified as class B in the Distribution System Security Standard (DSSS). The Al Bashir primary substation feeds a 35-distribution transformer with different capacities. The Al Bashir farm fed from distribution transformer 52, which has a 1000-kVA capacity. This transformer feeds multiple customers, including the Al Bashir farm with the highest load. The average power kW of Al Bashir primary substation and the distribution transformer-52, for the period of investigation used in this study (January to October, 2018 and 2019, respectively) are shown in Table 3. From Table 3, the average load of the Al Bashir network varies in both years for the considered months.

Table 4: Export and import of average power from May to October 2019.

Month	Export—average power (kW)	Import—average power (kW)
May	43	87
June	20	124
July	25	110
August	48	70
September	29	114
October	43	74

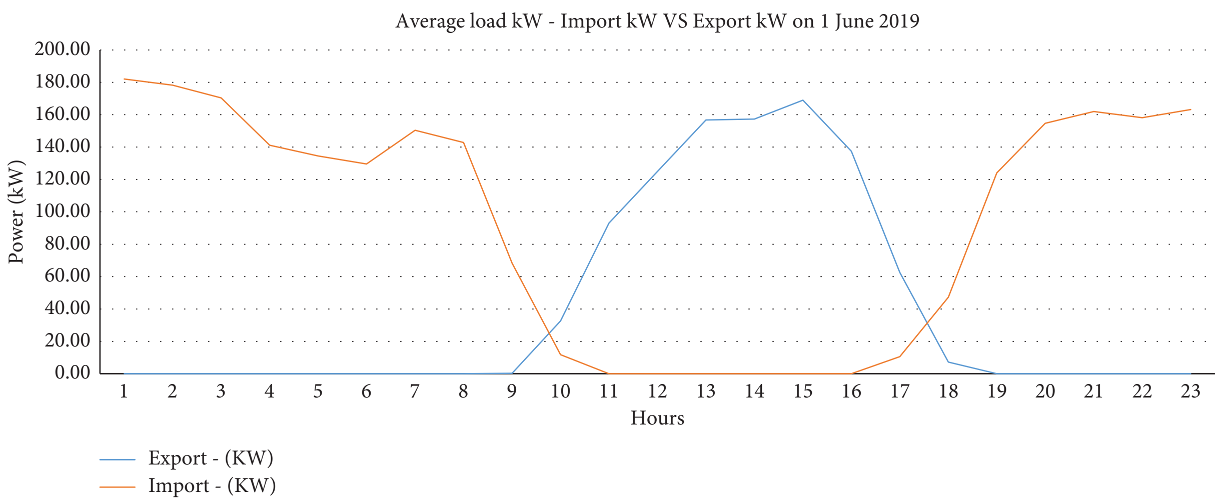

Figure 7: Average load kW-Import kW versus Export kW on 1 June 2019.

In mid May 2019, the Al Bashir farm's PV system started operation to cover its loads and export the surplus power to the national power grid. The solar PV system consists of seven panels with individual inverters as shown in Figure 6. The single-stage inverter configuration described in Figure 4(a) is employed in the Al Bashir solar farm. The connection point between the PV system and the MZEC network is at the meter panel at the customer boundary. The smart meter measures the export and import load from the customer to the power grid or vice versa. Table 4 shows the average power kW from the months of May to October 2019, in the course of the study.

7. Evaluation of the System Performance

In order to understand the impact of the penetration of the solar PV system into the power grid, it is required to analysis the load behavior of the customers. After energizing the Al Bashir farm's solar PV system in mid May 2019, most of the loads of the customers were supplied by the installed solar PV system. Figure 7 shows the load behavior of Al Bashir farm from 1st June 2019 to 30 June 2019, after installing the solar PV system in the month of June 2019. It is obvious from Figure 7, that the customers still import power from the grid system and sometimes export some power to the grid during the day. It is apparent from Figure 7 that the customers export power to the grid from 9:00 a.m. to 6:00 p.m. and import power from the national power grid, the rest of the day. This behavior can be understood by mentioning the fact that the daily consumption of the customers is low at daytime because most of people are in their various places of work. On the other hand, the load becomes high at night because most of the consumers are backing home. This scenario would almost be repeated all day, as shown in Figure 8. Figure 9 reflects that the maximum export power happened in August 2019, after installing the solar PV system in May 2019, and the minimum export power was in June 2019. The responses in Figure 9 were due to the customers' consumption behavior.

Figure 10 shows the average load at Al Bashir distribution transformer without solar PV in 2018, and with solar PV in 2019. In Figure 10, the response of the average load in the distribution transformer DTX-52 is slightly different for the years 2018 and 2019, respectively. Based on the installation of the solar PV in May 2019, the load decreased to 400 kW, as compared to 2018, when the load was 700 kW. This difference shows that most of the Al Bashir farm's load is fed from the solar PV system, except some power exported to the power grid as discussed earlier.

Figure 11 shows the average load at Al Bashir primary substation without solar PV in 2018 and with solar PV in 2019. The change in the load curve at Al Bashir primary substation between 2018 and 2019 is clearly observed in Figure 11. The load started to drop in May with the penetration and synchronization of the solar PV system into the power grid. The average peak load decrease from 2018 to 2019, after installing the solar PV system, is around 2%.

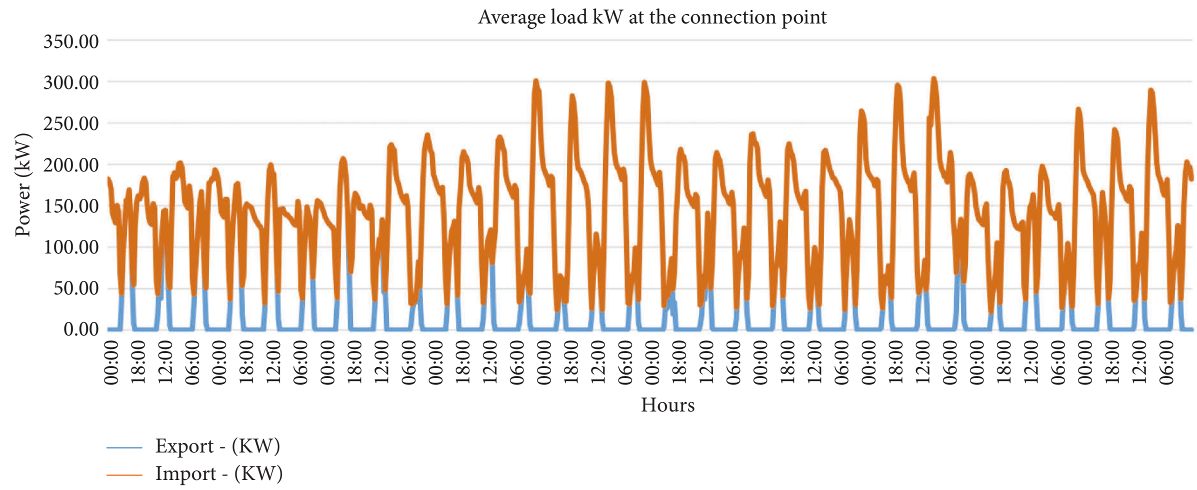

Figure 8: Al Bashir load behaviour after installing PV system.

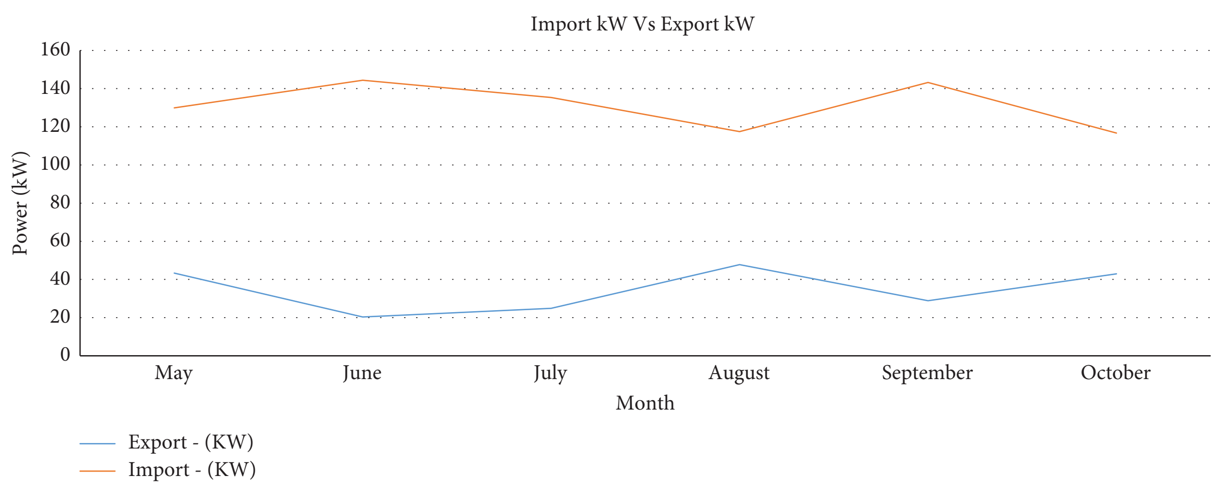

Figure 9: Average load import versus export.

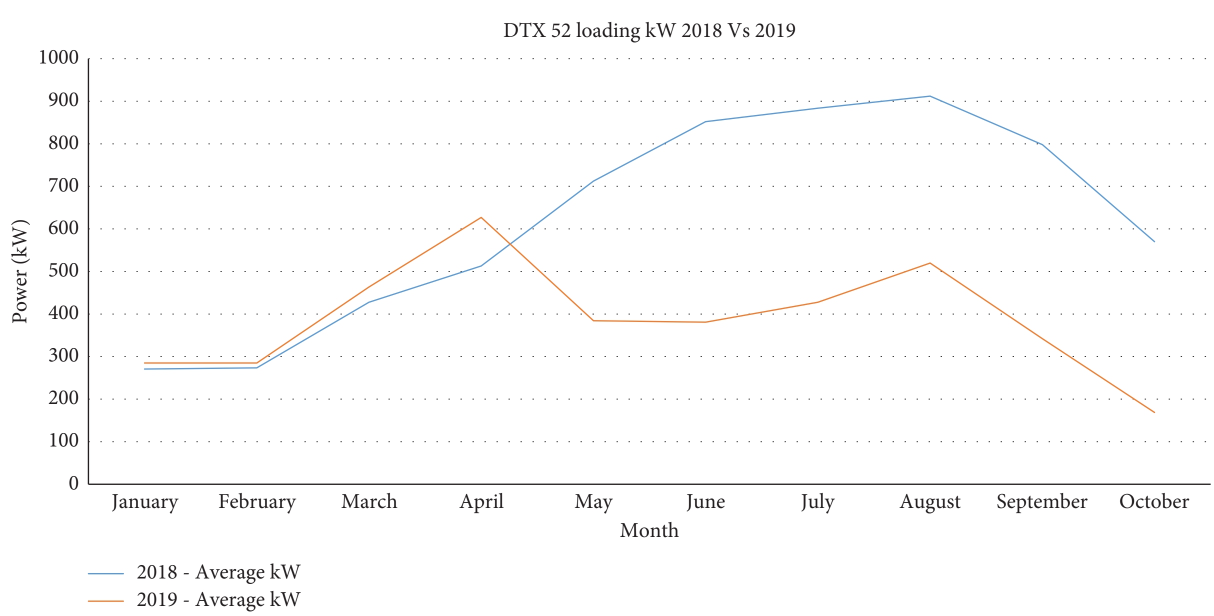

Figure 10: Average load at Al Bashir distribution transformer without (2018) and with (2019) solar PV.

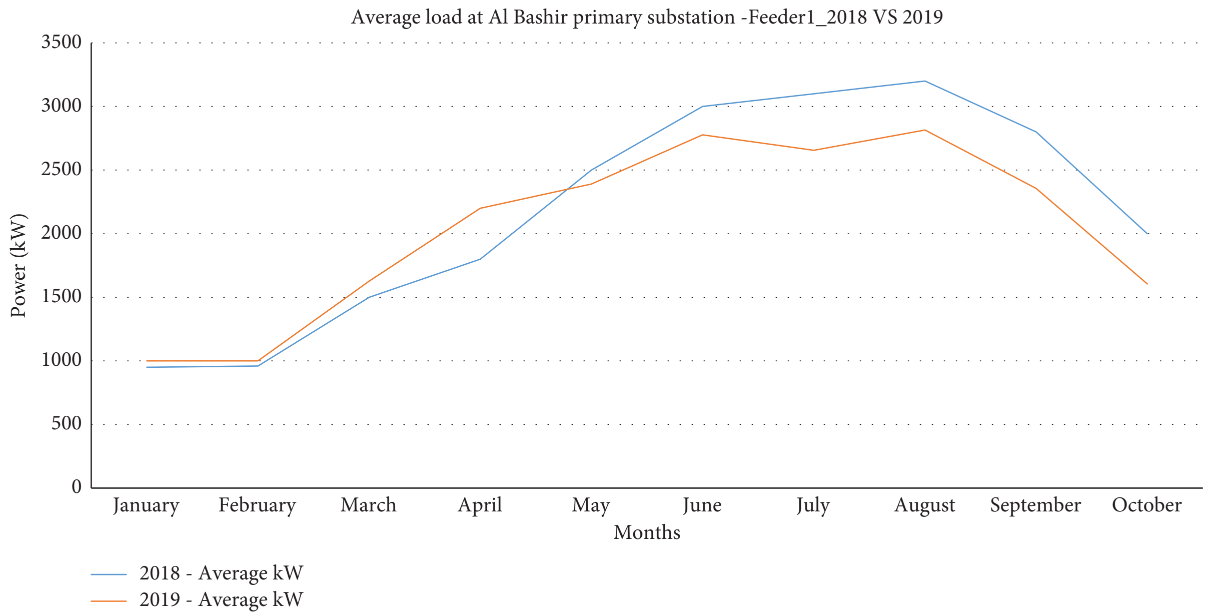

Figure 11: Average load at Al Bashir primary substation without (2018) and with (2019) solar PV.

Based on the above analysis, this study has been able to deduce the following. The response of the load behavior in the power grid changed after the installation of the solar PV system. The best time to export power is during the day between 9 a.m. and 6 p.m. The maximum load of Al Bashir primary substation decreased in 2019 and that will give spare power to feed more customers, which will be reflected in the Capital Expenses (CAPEX) cost. This means, there is no need to invest more in distribution transformers, thus, reducing their installations in the power grid. This is apparent since there would be a possible reduction of the load in the network from 80% in 2018, when there were no solar PV installations in the power grid, to 40% in 2019, with the penetration of solar PV in the power grid, based on Figures 10 and 11. Consequently, in the near future, new consumers could be fed from the excess solar PV power in order to save cost.

8. Conclusions

In this paper, a study of the effect of the penetration of solar PV on the load behavior in a grid-connected system was carried out. The loads in the Al Bashir power substation, connected to the Mazoon Electrical Company (MZEC) power grid in the Sultanate of Oman were used as a case study. The system variables of the grid were analyzed before and after installing the solar PV system. The obtained results demonstrate that installing solar PV systems on the power grid may affect the load behavior, which consequently affects MZEC's investment plans. In addition, the export of power from the solar PV system may affect the electrical network components like distribution transformers. The maximum load of the primary substation employed in the case study was decreased when the solar PVs were installed. Consequently, creating room for excess power to feed more customers, and the same time saving cost. The results obtained could help in drawing plans that are beneficial to the electricity companies, in reducing the number of distribution transformers in the power grid due to the penetration of solar PV systems.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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