# COMPARISON OF VARIOUS REACTIVE POWER DEFINITIONS IN NON SINUSOIDAL NETWORKS WITH THE PRACTICAL DATA OF ELECTRICAL ARC FURNACE

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## ABSTRACT

*In the non sinusoidal networks, seven of the most famous power decompositions, proposed by Budeanu, Fryze, Kimbark, Shepherd and Zakikhani, Sharon, Kusters and Moore, and Czarnecki are widely recognized. In this study all of above reactive power definitions are simulated in MATLAB software. By using some statistic indices such as average and standard deviation applied to a huge number of data collected from eight Electric Arc Furnaces (EAFs) installed in Mobarakeh steel industry, Isfahan, Iran, the reactive power definitions are compared to each other from different ways. Also the mean of the seven famous definitions is considered as criteria and the farness of various definitions from it are compared to each other using proposed Mean Farness from Q, (MFQ) and Mean Farness from D, (MFD) indices.*

## INTRODUCTION

The reactive power has a unique and well-known definition in the linear circuits with completely sinusoidal waveforms of voltage and current which can be calculated simply from the known equation $Q = VI \sin\phi$. But this equation doesn't fulfil non-sinusoidal conditions in the networks with nonlinear loads and distorted voltages and currents.

For the non sinusoidal networks, power decompositions proposed by Budeanu[1], Fryze[2], Kimbark[3], Shepherd and Zakikhani[4], Sharon[5], Kusters and Moore[6], and Czarnecki[7] are widely recognized.

In the other hand electric arc furnaces (EAFs) are widely used in today's industry because of their productivity, precision, flexibility and some advanced applications. An AC electrical arc furnace is an unbalanced, non-linear and time-varying load that can introduce serious power quality problems to its nearby power systems [8], [9].

To compare the reactive power definitions using statistic indices a practical non linear and non sinusoidal load is needed. Since melting process of arc furnace is a stochastic process, EAFs data could be an appropriate choice for comparing various reactive power definitions from different ways to each other.

In this study, some of the important characteristics of reactive power at pure sinusoidal conditions [10] are compared for various definitions of reactive power in the non sinusoidal conditions. Also the above definitions, are simulated in MATLAB software and applied to the real data recorded from Mobarakeh steel industry in Isfahan/Iran. Data recorded at the primary side of EAF transformers, collected for a considerable number of melting processes in about three months. Comparing different definitions, some statistic indices such as standard deviation and mean value and proposed MFQ and MFD indices are used. Results show that some definitions have a higher average of calculated reactive power and have benefits to the electric companies and others have smaller and have benefits to the customer.

## REACTIVE POWER CHARACTERISTICS AT SINUSOIDAL CONDITIONS

The most important reactive power characteristics at completely sinusoidal conditions are as follows [10]:

1- If the reactive power is reduced to zero, the power factor will be unity.

2- The reactive power completes the power triangle, $S^2 = P^2 + Q^2$.

3- The sum of all reactive powers in a node is zero.

4- Reactive power can be positive or negative (the sign specifies whether a load is of inductive or capacitive type).

5- Reactive power can be reduced to zero by inserting inductive or capacitive components.

6- The reactive power can be calculated from the time domain wave forms of voltage and current.

Above characteristics are summarized in the following table for various reactive power definitions:

Table 1: Reactive power characteristics for various definitions

| definition \ Ch. No. | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|
| Sinusoidal conditions | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Budeanu | × | × | ✓ | ✓ | × | × |
| Fryze | ✓ | ✓ | × | ✓ | ✓ | ✓ |
| Kimbark | × | × | × | ✓ | × | × |
| Kusters & Moore | × | × | × | ✓ | ✓ | ✓ |
| Shepherd & Zakikhani | × | × | × | × | × | × |
| Sharon | × | × | × | ✓ | ✓ | × |
| Czarnecki | × | × | × | ✓ | ✓ | × |

## DATA RECORDS

Actual input voltage and current waveform data was recorded from eight EAFs installed in Mobarakeh steel industry, Isfahan/Iran.

This plant includes EAFs rated at 70 MW. The arc furnace transformers have the following ratings: 90-108 MVA, 63kV/230-720V, $Y/\Delta$ with x=6.5% based on voltage 720V. Supplying transformers of the plant are two three-phase, three-winding transformer banks rated at: 220/220/110 MVA, 400(Y)/63(Y)/33( $\Delta$ ) kV. The arc furnaces are compensated by a static VAr system (SVC) consisting of thyristor controlled reactors (TCRs) and fixed capacitors (FCs). The SVC and second, third, fourth and fifth harmonic filters have been connected to the tertiary winding of the supplying transformers. Single line diagram of the EAFs in Mobarakeh steel industry is shown in Fig .1.

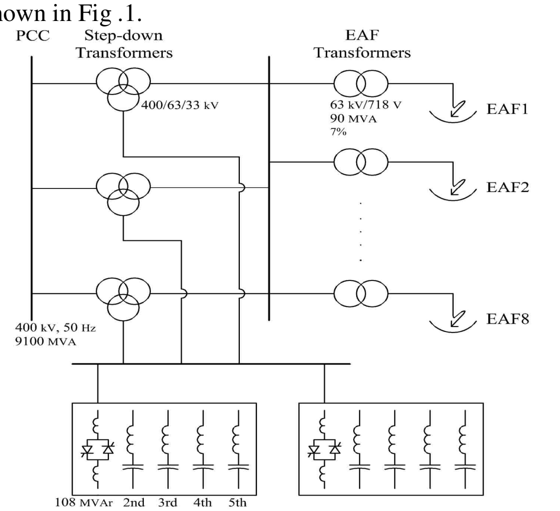


Fig. 1. Single line diagram of the EAFs in MOBARAKEH steel industry system

Data for eight EAFs including three-phase supply voltages and currents, measured in the primary and the secondary sides of the arc furnace transformers, was collected for scrapping, melting and refining stages of several melting processes during three months. Data records cover 10, 20, 50 and 100 seconds of real time furnace operation (Table 2). Each data set includes a number of samples with 128 $\mu$sec sampling time (the sample frequency is 7812.5 Hz).

Table 2: The total number of data records

| | 10 s | 20 s | 50 s | 100 s |
|---|---|---|---|---|
| Primary side | 345 | 6 | 50 | 20 |
| Secondary Side | 201 | 15 | 6 | 0 |

The reactive power is calculated per each cycle according to the various reactive power definitions. So for each recorded data it will be one time series. For example for each 10 sec data we will have a time series with the length of 500 samples for each definition. Hence for the 10 s data, there will be totally 345*500=172500 cycles of reactive power (Q) and distortion power (D).

## SIMULATIONS OF VARIOUS REACTIVE POWER DEFINITIONS USING MATLAB

In this paper, seven definitions of reactive power which are summarized in table 1 are simulated with MATLAB software. By using some statistic indices such as average and standard deviation applied to the data collected from EAFs and using some statistic indices, these definitions are compared to each other from different ways. Also the mean of seven definitions is considered as criteria and the farness of various definitions from it are compared to each other using proposed Mean Farness from Q, (MFQ) and Mean Farness from D, (MFD) indices. These indices and related figures and tables are as follows.

### MQ, MD

These indices for each data record determine the Mean of reactive power (MQ) over a specified time and also the Mean of Distortion power (MD). It means MQ and MD are the averages of reactive power and distortion power of each time series for each definition.

Figures 2 and 3 show the MD and MQ indices applied to a part of 10 seconds data records for various definitions belong to the EAF transformer primary side.

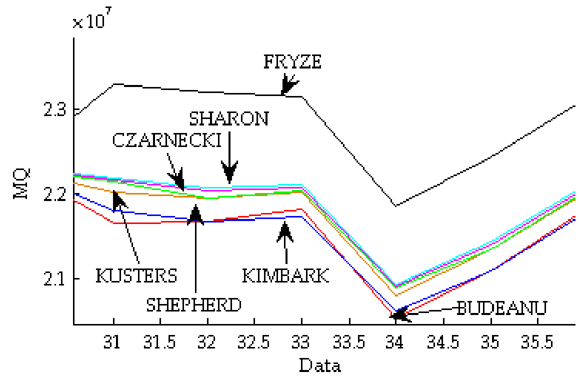


Fig. 2 MQ applied to a part of 10 seconds EAF data records for various definitions

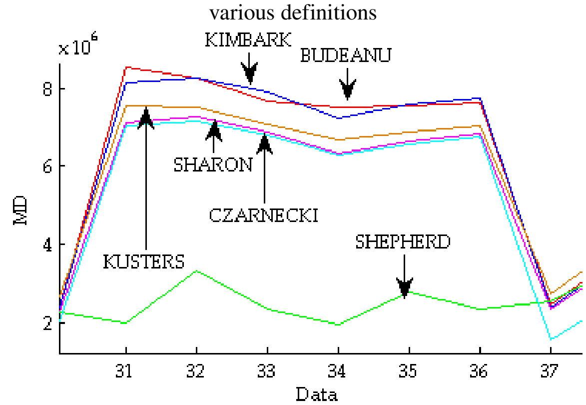


Fig. 3 MD applied to a part of 10 seconds EAF data records for various definitions

### SQ, SD

These indices determine the Standard deviation of reactive power, (SQ) and the Standard deviation of Distortion power (SD). It means SQ and SD are the Standard deviations of reactive power and distortion power of each time series for each definition.

Fig.4 and Fig.5 show SQ and SD indices applied to a part of 10 seconds data records for various definitions belong to the EAF transformer primary side.

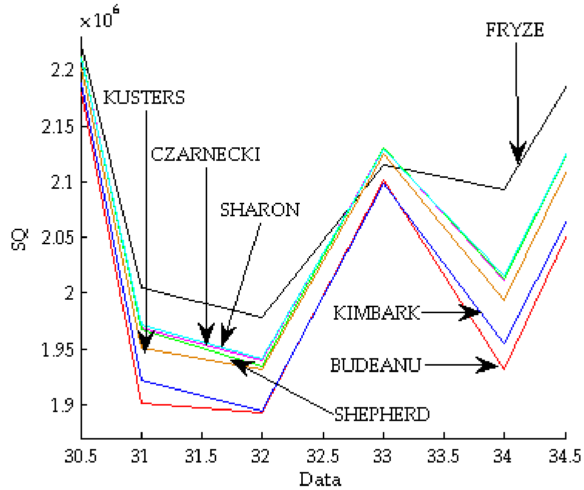


Fig. 4 SQ applied to a part of 10 seconds EAF data records for various definitions

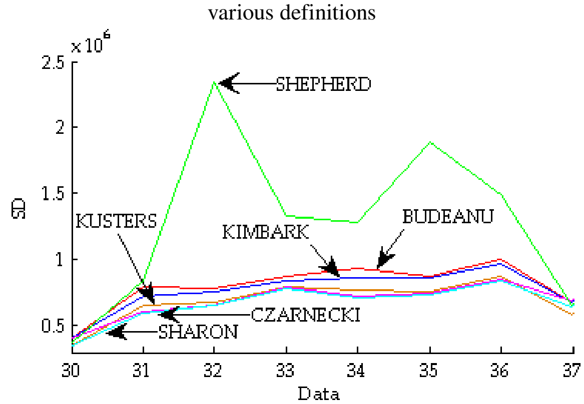


Fig. 5 SD applied to a part of 10 seconds EAF data records for various definitions

## MMQ, MMD, MSQ, MSD

MMQ, MMD, MSQ, MSD indices are the means of MQ, MD, SQ, SD parameters respectively over all the data records. Tables 3 and 4 show those indices for the 10 s, 20 s, 50 s and 100 s data of the EAF transformer secondary and primary sides respectively.

Table 3: MMQ, MMD, MSQ, MSD indices for various reactive power definitions for data records of the EAF transformer secondary side

| 10 sec record of secondary side of EAF transformer | | | | | | | |
|---|---|---|---|---|---|---|---|
| | Fryze | Budeanu | Kimbark | Kusters | Sharon | Shepherd | Czarnecki |
| MMQ*10^7 | 2.4638 | 2.3208 | 2.3243 | 2.3473 | 2.3599 | 2.3563 | 2.3622 |
| MMD*10^6 | 0 | 7.8662 | 7.8219 | 7.1126 | 6.7152 | 2.7557 | 6.6390 |
| MSQ*10^6 | 4.1329 | 4.0584 | 4.0628 | 4.1236 | 4.1238 | 4.1127 | 4.1215 |
| MSD*10^6 | 0 | 1.5757 | 1.4696 | 1.3855 | 1.3452 | 1.3157 | 1.3457 |
| 20 sec record of secondary side of EAF transformer | | | | | | | |
| MMQ*10^7 | 2.9343 | 2.7522 | 2.7565 | 2.7956 | 2.8091 | 2.8030 | 2.8123 |
| MMD*10^6 | 0 | 9.9738 | 9.8979 | 8.6463 | 8.2062 | 3.5227 | 8.1007 |
| MSQ*10^6 | 5.2564 | 5.2390 | 5.2333 | 5.3162 | 5.3272 | 5.3057 | 5.3250 |
| MSD*10^6 | 0 | 1.5337 | 1.4339 | 1.4126 | 1.3877 | 1.5946 | 1.3759 |
| 50 sec record of secondary side of EAF transformer | | | | | | | |
| MMQ*10^7 | 1.4800 | 1.3724 | 1.3756 | 1.3914 | 1.4043 | 1.3998 | 1.4068 |
| MMD*10^6 | 0 | 4.5384 | 4.5284 | 4.1797 | 3.7444 | 2.0893 | 3.6819 |
| MSQ*10^6 | 9.1202 | 9.2051 | 9.2035 | 9.2142 | 9.2193 | 9.2034 | 9.2143 |
| MSD*10^6 | 0 | 1.4158 | 1.2642 | 1.5267 | 1.2052 | 0.6553 | 1.2057 |

Table 4: MMQ, MMD, MSQ, MSD indices for various reactive power definitions for data records of the EAF transformer primary side

| 10 sec record of primary side of EAF transformer | | | | | | | |
|---|---|---|---|---|---|---|---|
| | Fryze | Budeanu | Kimbark | Kusters | Sharon | Shepherd | Czarnecki |
| MMQ *10^7 | 2.6578 | 2.5912 | 2.5929 | 2.5890 | 2.6004 | 2.6001 | 2.6165 |
| MMD*10^6 | 0 | 4.2611 | 4.1755 | 4.5584 | 4.0241 | 3.7109 | 3.1569 |
| MSQ*10^6 | 5.6505 | 5.7697 | 5.7686 | 5.7609 | 5.7172 | 5.7167 | 5.6733 |
| MSD*10^6 | 0 | 1.4822 | 1.4825 | 1.4367 | 1.4584 | 1.2210 | 1.5288 |
| 20 sec record of primary side of EAF transformer | | | | | | | |
| MMQ *10^7 | 2.3059 | 2.2962 | 2.2961 | 2.2925 | 2.2964 | 2.2963 | 2.3015 |
| MMD*10^6 | 0 | 1.6428 | 1.6504 | 2.1506 | 1.6347 | 1.7233 | 1.2017 |
| MSQ*10^6 | 1.6564 | 1.7036 | 1.7043 | 1.7014 | 1.6976 | 1.6976 | 1.6699 |
| MSD*10^6 | 0 | 4.2387 | 4.2015 | 3.3690 | 4.2426 | 4.1978 | 4.2585 |
| 50 sec record of primary side of EAF transformer | | | | | | | |
| MMQ *10^7 | 2.4870 | 2.4400 | 2.4401 | 2.4373 | 2.4495 | 2.4493 | 2.4607 |
| MMD*10^6 | 0 | 3.0967 | 3.0380 | 3.4930 | 2.9736 | 2.9401 | 2.2944 |
| MSQ*10^6 | 4.6244 | 4.7029 | 4.7162 | 4.6932 | 4.6603 | 4.6599 | 4.6268 |
| MSD*10^6 | 0 | 1.4816 | 1.5074 | 1.4062 | 1.4003 | 1.1485 | 1.4142 |
| 100 sec record of primary side of EAF transformer | | | | | | | |
| MMQ *10^7 | 2.7134 | 1.4168 | 1.4171 | 1.4149 | 2.7083 | 2.7082 | 2.7107 |
| MMD*10^6 | 0 | 1.6098 | 1.5633 | 2.2119 | 1.5284 | 1.6711 | 1.1055 |
| MSQ*(10^6) | 3.3047 | 3.3116 | 3.3116 | 3.3065 | 3.3118 | 3.3116 | 3.3062 |
| MSD*(10^6) | 0 | 4.0468 | 4.0407 | 3.4126 | 4.1095 | 3.9526 | 4.0510 |

## MFQ, MFD

As it said before for each data record there will be seven time series according to the seven definitions. The average of seven time series is considered as criteria and the farness of the different definitions from it is calculated. Hence we define two other indices, Mean Farness from Q, (MFQ) and Mean Farness from D, (MFD) as the following equations:

$$MFQ = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(AQ_i - Q_i)^2} \qquad (1)$$

$$MFD = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(AD_i - D_i)^2} \qquad (2)$$

For each data record, $Q_i$, $D_i$, $AQ_i$ and $AD_i$ are the $i$'th sample of time series related to the reactive power, distortion power and the average of seven definitions for reactive and distortion powers respectively. $N$ is the length of time series. Smaller MFQ and MFD values for each definition, means this definition is closer to the average of all.

Tables 5 and 6 show MFQ and MFD for EAF transformer secondary and primary sides respectively.

Table 5: The proposed MFQ and MFD indices for EAF transformer secondary side

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 10 sec record of secondary side of EAF transformer | | | | | | | |
| MFQ*10^7 | 10.524 | 9.5068 | 9.2194 | 5.5944 | 3.4715 | 4.1222 | 3.3784 |
| MFD*10^7 | - | 1.0185 | 0.9924 | 0.6857 | 0.5101 | 1.3177 | 0.4867 |
| 20 sec record of secondary side of EAF transformer | | | | | | | |
| MFQ*10^7 | 2.6525 | 1.7810 | 1.7246 | 0.8283 | 0.6207 | 0.6762 | 0.6667 |
| MFD*10^7 | - | 1.8828 | 1.8322 | 1.0655 | 0.8077 | 2.3023 | 0.7725 |
| 50 sec record of secondary side of EAF transformer | | | | | | | |
| MFQ*10^7 | 2.0317 | 1.3303 | 1.2729 | 0.9180 | 0.5805 | 0.6083 | 0.6096 |
| MFD*10^7 | - | 1.3627 | 1.3071 | 1.0030 | 0.6629 | 1.6582 | 0.6789 |

Table 6: The proposed MFQ and MFD indices for EAF transformer primary side

| | Fryze | Budeanu | Kimbark | Kusters | Sharon | Shepherd | Czarnecki |
|---|---|---|---|---|---|---|---|
| **10 sec record of primary side of EAF transformer** | | | | | | | |
| MFQ*10^7 | 9.0530 | 4.6114 | 4.1930 | 5.6918 | 3.6685 | 3.7561 | 4.4757 |
| MFD*10^7 | - | 3.7942 | 3.3562 | 4.9907 | 3.0077 | 4.5514 | 5.3389 |
| **20 sec record of primary side of EAF transformer** | | | | | | | |
| MFQ*10^7 | 5.0869 | 1.9092 | 1.9968 | 4.5907 | 1.9733 | 1.9968 | 3.0295 |
| MFD*10^7 | - | 1.5275 | 1.6616 | 4.1560 | 1.7308 | 1.7544 | 3.5581 |
| **50 sec record of primary side of EAF transformer** | | | | | | | |
| MFQ*10^7 | 1.6071 | 0.7887 | 0.7584 | 1.0745 | 0.6833 | 0.6845 | 0.8336 |
| MFD*10^7 | - | 5.9273 | 5.6741 | 9.0025 | 4.7573 | 6.7034 | 9.3513 |
| **100 sec record of primary side of EAF transformer** | | | | | | | |
| MFQ*10^7 | 5.4189 | 4.9138 | 4.8368 | 5.3939 | 4.8273 | 4.8367 | 5.1029 |
| MFD*10^7 | - | 3.8321 | 3.4623 | 10.5312 | 3.1889 | 4.2917 | 8.2350 |

## ANALYSIS OF RESULTS

The following results can be extracted comparing various reactive power definitions using the above tables:

1-Fryze's definition has the highest average of all reactive power definitions and has benefits to the electric companies.

2-Budeanu's definition has the smallest average of all reactive power definitions and has benefits to the customers.

3-Sharon's, Shepherd's and Czarnecki's definitions have closer results to each other and can be put in a category.

4-Budeanu's and Kimbark's definitions have closer results to each other and can be put in another category.

5-Czarnecki's distortion part of reactive power (D), has the smallest value between all definitions

6-Sharon's reactive power is the nearest definition from the average of all definitions.

7-Fryze's reactive power is the farthest definition from the average of all definitions.

Extracted results of comparing various reactive power definitions with the practical data of Mobarakeh Electrical Arc Furnaces are summarized in the table 7.

Table 7: Results of comparing various reactive power definitions with the practical data of Mobarakeh EAFs

| | |
|---|---|
| Maximum average reactive power calculated | Fryze |
| Maximum average reactive power calculated | Budeanu |
| Close to each other and put to a category | Budeanu - Kimbark |
| Close to each other and put to another category | Sharon - Shepherd - Czarnecki |
| minimum distortion power calculated | Czarnecki |
| Farthest definition to the average of all | Fryze |
| Nearest definition to the average of all | Sharon |

## Conclusions

Results of comparing various reactive power definitions show that Fryze's definition has the maximum average of reactive power calculated and considering the reactive power with this definition have benefits to the electric companies. On the other hand Budeanu's and Kimbark's definitions have the smallest average of reactive power calculated between all of the definitions and have benefits to the customer.

Our results show that Budeanu's and Kimbark's definitions have very close results and can be put into a category Also Sharon's, Shepherd's and Czarnecki's have close results and can be put into another category. Table 5 shows that Sharon's definition has the Smallest MFQ and MFD that means this definition is the nearest definition to the average of all.

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