Solving the Unit Commitment Problem Using Fuzzy Logic

Assad Abu-Jasser

Abstract—This paper presents an application of the fuzzy logic to the unit commitment problem in order to find a generation scheduling such that the total operating cost can be minimized while satisfying a variety of constraints. The optimization algorithm employed to solve the unit commitment problem benefits from the advantages of dynamic programming and the fuzzy logic approaches in the purpose of obtaining preferable unit combinations at each load demand. As a case study, the four-generating unit thermal power plant of Tuncbilek in Turkey is used. The purpose is to show that the fuzzy logic based approach achieves a solution to the unit commitment problem that is logical, feasible and with economical cost of operation which is the main objective of unit commitment. The results obtained by the fuzzy logic are tabulated, graphed and compared with that obtained by the dynamic programming. The outcomes show that the implementation of fuzzy logic provides a feasible solution with significant savings.

***Index Terms*—Dynamic programming, fuzzy logic, optimization, unit commitment**

I. INTRODUCTION

In all power stations, investment is quite expensive and the resources needed to operate them are rapidly becoming sparser. As a result, the focus today is on optimizing the operating cost of power stations. In the present world, meeting the power demand as well as optimizing generation has become a necessity. Unit commitment (UC) in power system refers to the optimization problem for determining the on/off states of generating units that minimize the operating cost subject to variety of constraints for a given time horizon. The solution of the unit commitment problem (UCP) is a complex optimization problem. The exact solution of the UCP can be obtained by complete enumeration of all feasible combinations of generating units, which could be huge number. The unit commitment is commonly formulated as a non–linear, large scale, mixed integer combinational optimization problem.

Review of UCP may be found in Padhy [1]. The dynamic programming (DP) method as in Snyder and Hobbs [2, 3] based on priority list is flexible, but the computational time suffers from dimensionality. As Merlin and Redondo, Lagrangian relaxation (LR) for UCP [4, 5] was superior to DP due to its higher solution quality and faster computational time. However, Dekranjanpetch said that numerical convergence and solution quality of LR are not satisfactory when identical units exist [6]. With the advent of heuristic approaches, genetic algorithm (GA) as Kazarlis [7], evolutionary programming (EP) as Juste [8], simulated annealing (SA) as Mantawy [9], and tabu search (TS) as Selim Shokri [10] have been proposed to solve the UC problems. The results obtained by GA, EP, TS and SA require a considerable amount of computational time especially for large system size.

The use of fuzzy logic has received increased attention in recent years because of its worth in dropping the requirement for difficult mathematical models in problem solving. Relatively, fuzzy logic employs linguistic terms, which deal with the causal relationship between input and output variables. For this reason, fuzzy logic approach makes it easier to manipulate and solve many problems, particularly where the mathematical model is not explicitly known, or is hard to solve. Moreover, fuzzy logic as a new technique approximates reasoning while allowing decisions to be made efficiently.

To achieve a good unit commitment planning under fuzzy approach, generation cost and load demand are all specified as a fuzzy set notation. Fuzzy Logic Technique is then applied to yield the desired commitment schedule. In order to demonstrate the superiority of this proposed approach, the power plant of Tuncbilek in Turkey with four-thermal generating units is chosen as a test system.

II. THE UNIT COMMITMENT PROBLEM

The unit commitment problem can be mathematically described as given in equation (1).

$$Min\, F_i(P_i^t, U_i^t) = \sum_t \sum_i [(a_i P^2 + b_i P + c_i) + SC_i^t\,(1 - U_i^{t-1})]U_i^t \tag{1}$$

where $F_i(P_i^t)$ is the generator fuel cost function in quadratic form, a_i, b_i and c_i are the coefficients of unit i, and P_i^t is the power generation of unit i at time t.

A. Problem Constrains

The minimization of the objective function is subjected to two kinds of constraints, namely: system and unit constraints and these can be summarized as follows:

A.1. System Constraints

Power Balance Constraints: to satisfy the load balance in each stage, the forecasted load demand should be equal to the total power generated for every feasible combination. Equation (2) represents this constraint where P_D^t represents the total power load demand at a certain period [11].

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Assad Abu-Jasser is with the Department of Electrical Engineering at the Islamic University of Gaza. Palestine.

$$\sum_{i=1}^{N} P_i^t U_i^t - (P_D^t) = 0 \qquad (2)$$

For each time period (T), the spinning reserve requirements R must be met and this can be mathematically formulated as in equation (3) [11]:

$$\sum_{i=1}^{N} P_i^{max} U_i - (P_D) = R \qquad t = 1, 2, 3 \ldots.T \qquad (3)$$

A.2 Unit constraints

Generation Limits

Each unit must satisfy its generation range and this certain rated range must not be violated. This can be accomplished through satisfying the formula in equation (4) [11]:

$$P_i^{min} U_i^t \leq P_i \leq P_i^{max} U_i^t \qquad (4)$$

$$i = 1, 2, 3 \ldots. N$$

where: P_i^{min} and P_i^{max} are the generation limits of unit i.

Ramp-Up and Ramp-Down Constraints

To avoid damaging the turbine, the electrical output of a unit cannot be changed by more than a certain amount over a period of time. For each unit, the output is limited by ramp up/down rate at each time period the unit is turned on/off and this can be formulated as in equations (5) and (6):

$$P_i^{t-1} - P_i^t \leq RD_i \qquad if \quad (U_i^t = 1)\ and\ (U_i^{t-1} = 1) \qquad (5)$$

$$P_i^t - P_i^{t-1} \leq RU_i \qquad if \quad (U_i^t = 1)\ and\ (U_i^{t-1} = 1) \qquad (6)$$

where: RD_i and RU_i are respectively the ramp down and ramp up rate limit of unit i.

III. DYNAMIC PROGRAMMING

Dynamic programming is a commonly used technique to solve the unit commitment problem. It acts as an important optimization technique with broad application areas where it decomposes a problem into a series of smaller problems, solves them, and develops an optimal solution to the original problem step-by-step. The optimal solution is developed from the sub problem respectively. In its fundamental form, the dynamic programming algorithm for unit commitment problem examines every possible state in every interval. Some of these states are found to be infeasible and hence they are rejected instantly. But even, for an average size utility, a large number of feasible states will exist and the requirement of execution time will stretch the capability of even the largest computers. Hence many proposed techniques use only some part of simplification and approximation to the fundamental dynamic programming algorithm. Dynamic programming has many advantages over the enumeration scheme. The main advantage is being the ability to reduce the dimensionality of the problem. Suppose we have found N units in a system and any combination of them could serve the single load. A maximum of $2^N - 1$ combinations are available for testing [11]. In the dynamic programming approach the following points are assumed:

- A state consists of an array of units with only specified units operating (online/turned on) at a time and the remaining unit/units is/are not operating (offline/turned off).
- The start-up cost of a unit is independent of the time it has been off-line (i.e. it is a fixed amount).
- There is no cost for shutting down a unit.
- There is a strict priority order, and in each interval, a specified minimum amount of capacity must be operating.

A feasible state is one in which the committed units can supply the required load and can meet the amount of capacity at each period [2, 12-13].

One could set up a dynamic-programming algorithm to run backward in time, starting from the final hour and studying it back to the initial hour. Conversely, one could set up the algorithm to run forward in time from the initial hour to the final hour. The forward approach has distinct advantages in solving the generator unit commitment problem. For example, if the start-up cost of a unit is a function of the time it has been off-line, then a forward dynamic-program approach is more suitable, using the previous history of the unit can be computed at each stage. There are other practical reasons for going forward. The initial conditions are easily specified and the computations can go forward in time as long as required.

IV. FUZZY LOGIC IMPLEMENTATION

Fuzzy logic provides not only a meaningful and powerful representation for measurement of uncertainties but also a meaningful representation of blurred concept expressed in normal language. Fuzzy logic is a mathematical theory, which encompasses the idea of vagueness when defining a concept or a meaning. For example, there is uncertainty or fuzziness in expressions like `large` or `small`, since these expressions are imprecise and relative. Thus, the variables considered are termed `fuzzy` as opposed to `crisp`. Fuzziness is simply one means of describing uncertainty. Such ideas are readily applicable to the unit commitment problem. The application of fuzzy logic allows a qualitative description of the behavior of a certain system, the characteristics of the system, and the response of that system without the need for exact mathematical formulation.

A. *Fuzzy Model for the Unit Commitment Problem*

The objective of every electric utility is to operate at minimal cost while meeting the load demand and spinning reserve requirements. In the present formulation, the fuzzy variables associated with the UCP are the load capacity of generator (LCG), the incremental fuel cost (IC), the start-up cost (SUC) as the input variables and the production cost (PRC) as the output variable. These fuzzy variables are presented and briefly explained in the following:

- *The load capacity of the generator* is considered to be fuzzy, as it is based upon the load to be served.
- *Incremental fuel cost* is taken to be fuzzy, because the cost of fuel may change over the period of time, and because the cost of fuel for each unit may be different.
- *Start–up costs* of *the* units are assumed to be fuzzy, because some units will be online and others will be offline. It is important to mention that the start costs, shut down *costs*, maintenance costs and crew expenses of each unit are included and lumped as a fixed value that is, the start-up cost. So, start-up cost of a unit is independent of the time during which the unit has been offline (it is a fixed amount).
- *Production cost* of the system is treated as a fuzzy variable since it is directly proportional to the hourly load.

Also, uncertainty in fuzzy logic is a measure of no specificity that is characterized by possibility distributions. This is similar to the use of probability distributions, which characterize uncertainty in probability theory. The possibility distributions attempt to capture the ambiguity in linguistically describing the physical process variables.

B. *Fuzzy Set Associated with the Unit Commitment*

After identifying the fuzzy variables associated with the unit commitment problem, the fuzzy sets defining these variables are selected and normalized between 0 and 1. This normalized value can be multiplied by a selected scale factor to accommodate any desired variable.

The sets defining the load capacity of the generator are as follows:

LCG = {Low, Below Average, Average, Above Average, High}

The incremental fuel cost is stated by the following sets:

IC = {Low, Medium, Large}

The sets representing the start-up cost are formulated as follows:

SUC = {Zero, Small, Large}

The production cost chosen as the objective function is given by:

PRC= {Low, Below Average, Average, Above Average, High}

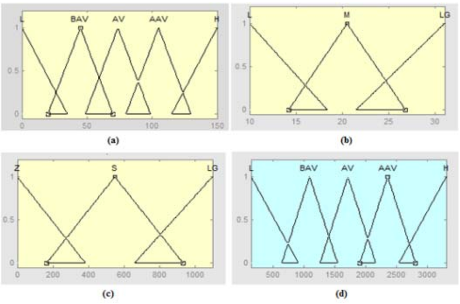


Fig. (1) . Membership function of input output variables

(a) LCG membership (b) IC membership

(c) SUC membership (d) PRC membership

Based on the aforementioned fuzzy sets, the membership functions are chosen for each fuzzy input and output variable as shown in Figure (1). For simplicity, a triangular shape is used to illustrate the membership functions considered here. Once these sets are established, the input variables are then related to the output variable by If-Then rules as described next.

C. *Fuzzy If-Then Rules*

If fuzzy logic based approach decisions are made by forming a series of rules that relate the input variables to the output variable using If-Then statements. The-If (condition) is an antecedent to the Then (consequence) of each rule. Each rule in general can be represented in this manner: *If (condition) Then (consequence).* It should be noted that the Load capacity of a generator, the incremental fuel cost, and the start-up cost are considered as input variables while the production cost is treated as the output variable. This relation between the input variables and the output variable is given as follows:

Production cost = {Load capacity of the generator} AND {Incremental fuel cost} AND {Start-up cost}

In fuzzy set notation this is written as $PRC = LCG \cap IC \cap SUC$. Hence, the membership function of the production cost, μ PRC is computed as follows:

$$\mu\, PRC = \mu\, LCG \cap \mu\, IC \cap \mu\, SUC$$

Or

$$\mu\, PRC = min\{\mu\, LCG, \mu\, IC, \mu\, SUC\}$$

where: μ LCG, μ IC and μ SUC are the memberships of load capacity of the generator, the incremental fuel cost, and the start-up cost, respectively.

Using the above notation, fuzzy rules are written to associate fuzzy input variables with the fuzzy output variable. Based on these relationships and with reference to Figure (1), the total sum of rules that could be composed is 45. This is because there are five subsets for load capacity of generator, three subsets for incremental cost and three subsets for start-up cost (5×3×3=45). For instance, rule 7 can be written as follows:

If (the load capacity of a generator is low, and the incremental fuel cost is large and the start–up cost is zero), then the production cost is low. So, the fuzzy results must be defuzzified by a certain defuzzification method after relating the input variable to the output variable as listed in Table 1. That is called a defuzzification process to achieve crisp numerical values.

Note: Choosing the memberships and related logical rules are done in a subjective manner. Hence the variable "load capacity of a generator" can be divided into five zones while the variables “incremental fuel cost” and start-up” into three zones.

D. *Defuzzification Process*

Defuzzification is the transformation of the fuzzy signals back to crisp values. One of the most commonly used methods of defuzzification is the Centroid or center of gravity method. Using this method, the production cost is obtained as in equation (7):

$$Production\ Cost = \frac{\sum_{i=1}^{n} \mu(PRC)_i \times PRC_i}{\sum_{i=1}^{n} \mu(PRC)_i} \tag{7}$$

where: $\mu\,(PRC)_i$ is the membership value of the clipped output and $(PRC)_i$ is the quantitative value of the clipped output and n is the number of the points corresponding to quantitative value of the output.

TABLE I: FUZZY RULES RELATING INPUT/OUTPUT FUZZY VARIABLES

Rule	**LCG**	**IC**	**SUC**	**PRC**	**Rule**	**LCG**	**IC**	**SUC**	**PRC**
1	L	L	Z	L	24	AV	M	LG	AV
2	L	L	S	L	25	AV	LG	Z	AV
3	L	L	LG	L	26	AV	LG	S	AV
4	L	M	Z	L	27	AV	LG	LG	AV
5	L	M	S	L	28	AAV	L	Z	AAV
6	L	M	LG	L	29	AAV	L	S	AAV
7	L	LG	Z	L	30	AAV	L	LG	AAV
8	L	LG	S	L	31	AAV	M	Z	AAV
9	L	LG	LG	L	32	AAV	M	S	AAV
10	BAV	L	Z	BAV	33	AAV	M	LG	AAV
11	BAV	L	S	BAV	34	AAV	LG	Z	AAV
12	BAV	L	LG	BAV	35	AAV	LG	S	AAV
13	BAV	M	Z	BAV	36	AAV	LG	LG	AAV
14	BAV	M	S	BAV	37	H	L	Z	H
15	BAV	M	LG	BAV	38	H	L	S	H
16	BAV	LG	Z	BAV	39	H	L	LG	H
17	BAV	LG	S	BAV	40	H	M	Z	H
18	BAV	LG	LG	BAV	41	H	M	S	H
19	AV	L	Z	AV	42	H	M	LG	H
20	AV	L	S	AV	43	H	LG	Z	H
21	AV	L	LG	AV	44	H	LG	S	H
22	AV	M	Z	AV	45	H	LG	LG	H
23	AV	M	S	AV					

TABLE II: DAILY LOAD DEMAND (MW)

Stage	Demand
1	168
2	150
3	260
4	275
5	313
6	347
7	308
8	231

TABLE III: PARAMETERS FOR THE FOUR-UNIT TUNCBILEK THERMAL POWER PLANT

Unit No.	Generation Limits		Running Cost			Start-up Cost		Ramp Rates	
	Pmin (MW)	Pmax (MW)	A ($\$/\text{MW}^2$.h)	B (\$/MWh)	C (\$/h)	SC (\$)	SD (\$)	RU (MW/h)	RD (MW/h)
1	8	32	0.515	10.86	149.9	60	120	6	6
2	17	65	0.227	8.341	284.6	240	480	14	14
3	35	150	0.082	9.9441	495.8	550	1100	30	30
4	30	150	0.074	12.44	388.9	550	1100	30	30

TABLE IV: GENERATION SCHEDULE OF THE FOUR UNITS AT TUNCBILEK THERMAL POWER PLant

Period	Demand (MW)	Unit Commitment				IC	Production cost (\$)	
		Unit 1	Unit 2	Unit 3	Unit 4		FL	DP
1	168	0	0	87.69199	80.3080	24.32	4449.65	4343.57
2	150	0	0	79.15353	70.84647	22.92	4148.06	3438.31
3	260	0	43.5162	110.6907	105.7931	28.09	6510.51	6736.43
4	275	16.6302	43.2777	110.0305	105.0615	27.98	6493.76	6848.95
5	313	18.9320	48.4999	124.4871	121.0809	30.35	7230.98	7747.68
6	347	20.9915	53.1724	137.4219	135.4141	32.48	7298	8815.98
7	308	18.6291	47.8128	122.5849	118.9731	30.04	6493.76	7596.66
8	231	0	39.2739	98.94667	92.77942	26.17	6409.98	5544.93
						Sum	49034.7	51072.5

D. *The Fuzzy Logic Procedures*

To solve the unit commitment problem, two types of variables are needed. The first variables are the units' statuses at each period $U_{i,t}$ which are integer or binary (0–1) variables, and the second variables are the units' output powers P_i^t, which are continuous variables that need to be determined [3]. This problem can be divided into two sub-problems: The first is a combinatorial optimization problem in *U,* while the other is a nonlinear one in *P.*

A Fuzzy based approach is proposed and implemented to solve this complicated optimization problem. The economic dispatch is simultaneously solved via a quadratic programming routine. Figure (2) shows the flowchart of the applied fuzzy approach. The major steps of this approach are summarized as follows: start by identify fuzzy input and output variables, then relate fuzzy input and output variables using fuzzy rules (If-then), determine feasible combinations of units considering given constrains and solve economic dispatch for these feasible combinations, and finally defuzzify the output variable (production cost) and repeat for all periods.

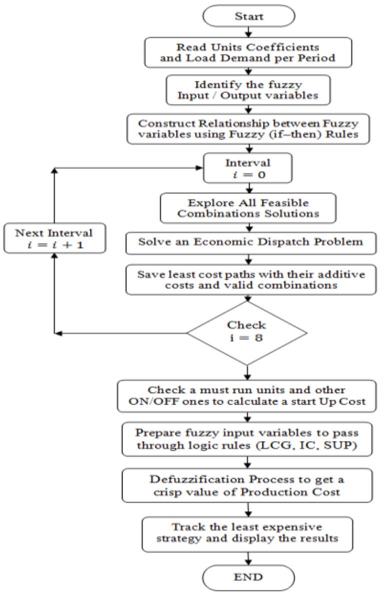


Fig. (2). Flowchart of the Fuzzy Approach

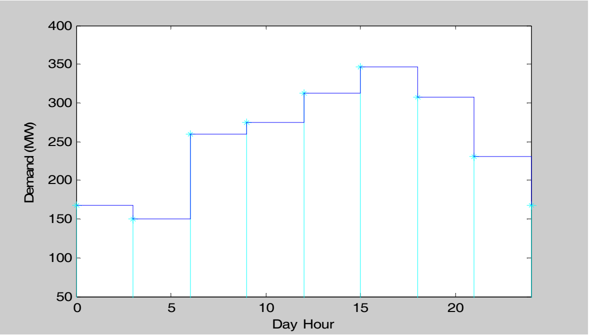


Fig. (3). Daily load demand

V. CASE STUDY

The Tuncbilek thermal power plant in Turkey with four generating units has been considered as a case study. A daily load demand divided into eight periods (three hours for each) is considered. Table 2 contains this load demand [14] while Figure (3) graphs this demand. The unit commitment problem will be solved applying the dynamic programming and fuzzy logic approaches and the results will be compared.

The parameters of these four generating units including the cost coefficients, the maximum and the minimum real power generation, the start-up cost, and the ramp rates of each unit are given in Table 3.

As mentioned, the production cost (PRC) is considered as the output variable while the load capacity of a generator (LCG), the incremental fuel cost (IC) and the start-up cost (SUC) are taken as input variables. It is important to note that the ranges of each subset are selected after some experiments in a subjective manner. For example, if the load range that can be served by the largest generator is between 0 to 150 MW, Then low LCG could be chosen within the range of 0–35 MW. This allows a relative and virtual evaluation of the linguistic definitions with the numerical values. Similarly, the subsets for other variables can be linguistically defined and it is clear that the range of LCG and PRC is wider than IC and SUC. Therefore five zones are made for both LCG and PRC fuzzy variables and three zones for the narrow variables (IC and SUC).

VI. SIMULATION RESULTS

An algorithm using the fuzzy logic for the unit commitment problem of the four-generating units at the Tuncbilek thermal power plant in Turkey is formulated. A Matlab computer program to provide a solution to the problem is also developed. The results obtained by the fuzzy logic approach provide crisp values of the production cost in each period for every given fuzzy input variables. The complete set of results obtained for the four-generating units are summarized in Table 4.

The fuzzy logic approach provides a logical and feasible solution for every time period. For each period, the sum of the unit commitments equals the load demand. The production costs obtained by the dynamic programming and the fuzzy Logic are shown in the last two columns of Table (4). The incremental fuel cost of the four units during the eight-time periods is depicted in Figure (4).

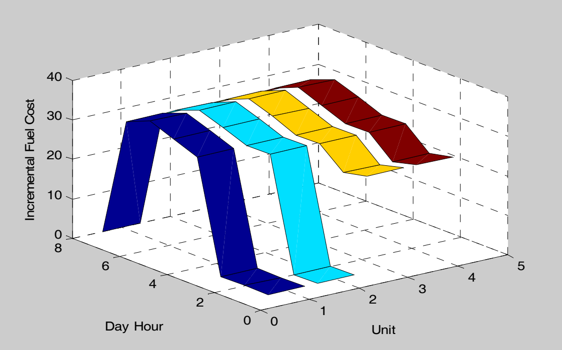
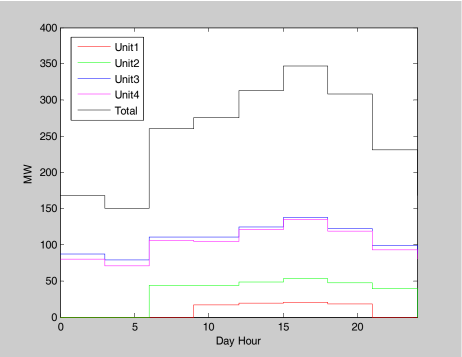
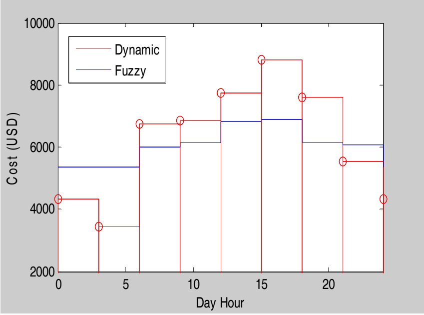


Fig. (4). Units incremental fuel cost

The load demand and units' commitment along with a comparison between the production costs obtained by the dynamic programming and fuzzy logic approaches are shown in Figure (5).



(a)



(b)

Fig. (5) Load demand and Unit Commitment and production cost
a) Demand and Units' commitment b) Production costs

VII. CONCLUSION

The primary objective has been to demonstrate that if the process of the unit commitment problem can be described linguistically, then such linguistic descriptions can be translated to a solution that yields a logical and a feasible solution to the problem with better results compared to dynamic programming. This solution to the unit commitment problem using fuzzy logic is successfully obtained and the best plan from a set of good feasible commitment decisions has been accomplished. The output results show that it is possible to get some improvements by fuzzy logic approach.

Moreover, the results show that the fuzzy logic provides a valid and a feasible solution to the unit commitment problem while satisfying all constraints for each time period. For the same unit commitments and the same incremental fuel cost, the production costs obtained by the fuzzy logic are higher in the first two and in the last time periods. In the remaining time periods, the production costs obtained by the fuzzy logic are lower than those obtained by the dynamic programming. For the eight-time periods, the overall production cost is lower when the fuzzy logic approach is employed.

The savings in the production cost of the small capacity thermal power plant of Tuncbilek in one day is $2037.8 and this makes the annual savings to reach about $750,000. It is strongly believed that as the capacity of the power plant increases the savings in the production cost also increases and this justifies the use of fuzzy logic to handle the unit commitment problem.

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Assad Abu-Jasser received a Bachelor degree from Helwan University – Cairo, Egypt in 1984, a master's degree from Rensselear Polytechnic Institute, Troy – NY, USA in 1990, and a PhD from the University of Bremen, Germany in 1998. Mr. Abu-Jasser worked as a Technical Instructor at the UNRWA Gaza Vocational Training Center in the years between 1985 and 1993. Since 1998 he is working as Assistant Professor at the department of electrical engineering at the Islamic University of Gaza. His research interests are Power Quality, Power System Operation and Optimization, and Renewable Energy.