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An Optimal Adaptive Control Strategy for Energy Balancing in Smart Microgrid Using Dynamic Pricing

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ABSTRACT Energy balancing in smart microgrid plays a vital role to improve the reliability and resolves the load shedding problem to ensure consistent energy supply. However, energy balancing is challenging due to uncertain and intermittent nature of renewable energy integrated in smart microgrid. To solve such problems, dynamic energy pricing mechanism is developed that maintain energy balance for overcoming the gap between demand and supply. Thus, the particle swarm optimization based super twisting sliding mode controller (PSO-STSMC) is developed which uses dynamic energy pricing to control renewable energy resources' generation according to the consumers' demand for real time closed loop energy balancing in an energy market. The proposed PSO-STSMC based model is compared with existing models like proportional integral derivative (PID) controller, proportional integral (PI) controller, proportional derivative (PD) controller, and fractional order proportional derivative (FO-PD) controller and the optimized models of the particle swarm optimization based proportional integral (PSO-PI) controller and particle swarm optimization based proportional integral derivative (PSO-PID) controller. Simulations results demonstrate that energy price regulation by PSO-STSMC consistently controls the elastic demand for real time energy balancing.

INDEX TERMS Smart grid, dynamic price server, elastic demand, renewable energy sources, dynamic energy price, elastic demand, demand side load management, energy balance, super twisting sliding mode controller.

I. INTRODUCTION

Electricity demand is rising and the traditional energy resources are depleting thus, a sustainable production that is dependent on renewable energy sources is needed [1]. The renewable energy sources are more sustainable and cheaper than the conventional sources of energy [2]. They generate the clean energy without the damaging effects on environment as the harmful gases emission in surroundings are negligible. The energy generated by renewable sources shows the random fluctuation due to climate change [3]. For instance, climate and environmental conditions disturb wind, solar, geothermal, tidal, ocean thermal and other renewable energy generation sources [4].

Future smart grids will contain integrated diverse renewable energy and distributed generation systems [5]. Hence, with integration of diverse energy generation resources power grids will be more volatile in terms of energy supply due to fluctuations and uncertainties in energy generation and trading processes for consumers [6]. Consequently, the smart grids should be capable of demand responsive management systems to tackle these fluctuations in energy generation

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TABLE 1. Abbreviations, symbols and terms.

Abbreviations	Full form
D	Energy demand
S	Energy supply
DR	Demand response
PID	Proportional integral derivative (controller)
FO-PI	Fractional order proportional integral (controller)
FO-PD	Fractional order proportional derivative (controller)
STSMC	Super twisting sliding mode controller
PSO-STSMC	Particle swarm optimization with super twisting sliding mode controller
DSLM	Demand side load management
S/D	Supply to demand ratio
α	Virtual demand rate
D_s	Virtual demand
τ	Time constant
d	Degree of polynomial
a_i	Coefficients polynomial p
S_d	Energy production model
p	Energy unit price
K_p	Proportional gain
K_i	Integral gain
K_d	Derivative gain
S_T	Overall energy production
C_{max}	Installed maximum capacity
G_j	Net production of energy by jth source type
$C_{max,j}$	Maximum capacity of renewable source for energy generation
$p_{0,j}$	Average cost required for energy production by jth source type
S_j	Production model for source type j
T_j	Mean time to reach maximum capacity production volume
p_c	Per unit price for consumers
λ	Fractional operator in FO-PD controller

system in real time [7]. Recent works shows effectiveness of demand response based demand side energy management systems in energy balancing in renewable energy integrated smart grid [8]. Whereas, dynamic energy pricing can also influence the energy generation and demand of consumers [9]. Recent research work also presented several energy pricing based energy management mechanism which evaluated the effectiveness of using energy price as control signal for the energy management [10]. There is an increasing trend in the research work which proposes energy management schemes for the efficient utilization of the renewable energy and fulfill consumers' energy demand [11]. Such energy management schemes facilitates the smart grid operation which not only increases the reliability but also enhances the communication between supplier and consumer through AMI for efficient utilization of the available resources [12]. In this study, with the framework of the demand side energy management system, a closed loop system is evaluated for the purpose of reliable and automated energy balancing in a energy market. The optimal adaptive controller consisting of the PSO algorithm and STSMC controller which essentially regulates the pricing signal in order to attain energy balancing. Hence, making the smart grid achieve energy balancing autonomously. However, the applications of the PSO tuned STSMC is not evaluated for the purpose of the generation control is recent studies. Hence, there is a gap in the research work to utilize the optimal robust controller based strategy for the purpose to regulate the energy price of the energy market and consequently gaining and maintaining energy balance. For performing energy price regulation in closed loop, the dynamic price server gets the load side consumers' demand data and regulates the instantaneous prices of energy to the grid to achieve the demand and supply balancing. Also, the current control strategies consists of manually tuned classical controllers results in volatile pricing signal. Hence, making the demand and generation fluctuating due to volatility in the pricing signal and making the energy price signal not feasible for the energy markets. Thus, the smart grid's energy market gets an energy balance situation by dynamic pricing regulated by the PSO-STSMC. Moreover, the validation of deploying PSO-STSMC controller in an energy market, the results are compared with the manually tuned and Genetic Algorithm (GA), and Differential Evolution (DE) based tuned classical controllers' responses.

In order to decrease the electricity demand and supply difference (e), we implemented (PSO-STSMC) in closed loop system, so that, the consumers' demand can be controlled. The system's working is summarized like as:

- The closed loop feedback error, that's referred to as as balance error (e) is reduced by the STSMC controller.
- STSMC controller gives the price (p) signal to drive the plant.
- The closed loop maintains a critical position to create the stability between generation and demand when the error between them is nearly same to zero.
- For simulations, our model is designed in MATLAB/ Simulink environment, which is composed of STSMC and PSO-STSMC and a dynamic pricing demand response model with generation feedback. The proposed model is applied on an example of smart microgrid integrated with seven renewable energy sources solar, wind, tidal, oceanthermal, geothermal, biogas and hydropower to control closed-loop elastic demand of consumers.
- The achievement of the proposed STSMC-based model is clearly appeared by its comparison to the response

of the models like PI controller and PID controller, when demand is in normal state and with PD controller and FO-PD controller for peak and dip demand. In the scenario of optimization the performance of PSO-STSMC is compared with PSO-PID and PSO-PI. The results describes that the our proposed scenario of STSMC/PSO-STSMC is better in performance for energy balancing by using dynamic energy price.

The organization of the work is as follows: Introduction is explained in section I. Section II describes related work, problem statement in Section III, overview of existing and proposed technique is given in Section IV, whereas in Section V closed loop energy management model is discussed. In Section VI simulation results and comparative study is carried out moreover, performance evaluation is also demonstrated. Finally, section VII conclude the entire work.

II. RELATED WORK

A lot of work has been conducted for load management in smart grid using dynamic energy pricing, some of them are listed as follows: Some techniques like the PID closed loop control system can adjust the price of energy online to counter dynamically and instantaneously the demands of load side, but there is the poor control for integration of distributed energy sources and large time delay process [13]. FO-PI controller regulates the energy price and maintain the energy balance. Automated energy balancing is the major objective of applying fractional order PI technique. It is applied for market management of energy and not verified experimentally [14]. Price changing is an important procedure for the smart grid which keeps up the balance between energy production and utilization with the help of STSMC in close loop system. The load changing, shifting, and modifying strategies according to the price are helpful for managing the load on consumers' side. If this technique is applied with particle swarm optimization then it can give better results [15]. Demand side management is in such a way that improves the reliability of consumers to supply them energy without any shortage. Game theory algorithms is the applied technique for systems operation. The model performance is only related to demand side load management [16]. Broadcasting of dynamic energy price signals for controlling consumer's demand is a suitable and easy way. In smart grid community, PI controller is used to regulate the energy price. So, the net energy demand can be controlled to respond fluctuation of renewable energy generation. However, PI controller is unable to improve the stability and reduce the instant energy demand overshoot [17]. Classical and fractional order controllers are also widely used in the power grid for the purpose to remove high disturbance and noise in voltage and current wave forms. Whereas provides an acceptable damping during the operation of power system at the output [18]–[20]. However our approach of employing an adaptive PSO-STSMC regulates the energy pricing signal for the energy market to efficiently utilize the available renewable energy and meet consumers' demand.

The most effective electricity flow manage method for a residential electricity network (RELN), because of the growing significance of demand-side assets in the electricity marketplace which includes of a little amount of homes, depends on the idea of load-side management. Especially, a kind of most effective and dynamic RELN electricity consumption scheduling framework is managed to reduce the entire operational cost, while fully observing about the output forecast error of renewable energy sources (RESs), the load preference of consumers and the situation of the electricity storage system. This load control strategy is limited only to domestic areas [21]. The graphical user interface (GUI) is the technique to maintain check and balance of the appliances status and condition, energy utilization and to calculate the per unit cost of energy. Hardware results shows the benefits of the proposed DSM algorithm [22]. The objective of DSM is to improve energy efficiency by using better materials, over smart energy tariffs with convincing for specific utilization patterns, up to the best real-time control of renewable sources. The major overview and a taxonomy is obtained by this paper for DSM and various types of DSM are discussed in it [23]. A persuasive smart energy management system (PSEMS) which gives relaxation to poor and middle class consumers. The PSEMS uses an algorithm based on mild modified intrusive genetic algorithm (MMIGA), technique. The PSEMS provides the better chance to domestic user to make choice regarding the use of electricity. Reducing electricity bill so that electricity should be useful for them [24]. The simulation's scenario indicate that the proposed energy management system (EMS) is capable to save the energy in microgrid and related domestic areas. It reduces energy consumption costs accordingly, but also to satisfy user's reliability by operational management of both demand and supply sides. In this scenario PI controller technique is applied [25]. This work provides a consumption side energy management technique which is done by applying heuristic-based evolutionary algorithm (EA) [26]. The proposed technique helps to manage the load on consumers side. This can balance the demand and supply and would also decrease the maximum demand along with load shifting, thus the system becomes efficient. Load side management for load shifting based on heuristic optimization algorithm is a major technique applied in this scenario. The proposed optimization algorithm has objective to shape the final load curve as near to possible to the desired load curve. The limitation of this strategy is compliance in the number of shift able loads in the system, which users are willing to use at any instantaneous time [27]. An efficient home energy management controller (EHEMC) based on genetic harmony search algorithm (GHSA). The major goal is to reduce electricity expense, peak to average ratio (PAR), and enhances the consumers' easement [28]. The applied technique is "Real time prices derivation from LMPs" for the stabilization of supply and demand. Its important advantage is the control of extreme price volatility. The key demerit is the instability of close loop system by market's LMPs [29]. The applied technique is home energy management (HEM) controller design by wind driven optimization (WDO) and genetic algorithm (GA). This technique is applicable on domestic level load management. The benefit to the consumers is to reduce electricity bills. However its application are bounded at residential level only [30]. Although different system have vital role for demand side energy management. However they are inter linked with some drawbacks too. some of them are bounded to only using single parameters to show their required result. To get the result more realistic random uncertainty value is added. Some system are limited to set energy prices online to tackle dynamically and instantaneously the demands of grid energy consumers. It is just numerically demonstrated that the control of power generation using dynamic pricing can maintain the best price point of demand and supply curve.

The above discussed references have the problem of decision making that leads to uncertainty in market conditions. For solving this problem, the smart grid in upcoming time will have to be flexible and shows the quick and sharp response to the fluctuation and uncertainty in demand or generation of energy. Our proposed model of PSO-STSMC, is the reliable and autonomous technique for the energy market which is useful for both consumers and energy supplying companies. It can be applicable at international energy market price management not just at residential level but also for commercial and industrial sector. Fluctuating renewable energy generation by the distributed renewable energy sources is following the elastic demand at all time through dynamic energy pricing. By applying our proposed technique the stability of closed loop energy system is maintained. The drawbacks of above mentioned research can be easily overcame by applying PSO-STSMC. More detailed literature review with the methodology adopted, objectives, achieved results and limitations are listed in the Table 2.

III. PROBLEM STATEMENT

The RESs are dependent on the climate or weather condition which can easily affect the power generation and may disrupt the continuous energy supply to the end user [31]. Moreover, there is elastic demand of consumers along with fluctuating supply of renewable sources, they lead to uncertainty and instability in energy market [32]. Demand side management is an important strategy to overcome such unreliable situation for creating the energy balance [33]. In this regard authors presents, an energy market management based on closed loop elastic demand control scheme by means of dynamic price signal broadcasting. A PID controller structure is used to regulate energy price signals for demand response agents of smart grid community [34]. Thus, total energy demand can be governed to respond fluctuation of renewable energy generation. Single techniques of PID, PI and fractional order PI is applied for energy balancing or demand side load management [35]. Multi techniques are well suited, through them we can observe the demand response and judge the best one scheme for energy balancing. Besides this only the parameter of dynamic price is applied for energy balancing. The demand side management by piecewise linear demand function is not so trustworthy, because the demand shows rise and fall at any instant and supply of distributed renewable sources is fluctuating as well. So, if the demand is in any uncertain or random situation the supply should trace it, then in such a way the reliable energy balance can be well developed.

IV. EXISTING AND PROPOSED SYSTEM METHODS

The role of different controllers is under consideration for balancing the demand and supply. PID, and ID controller parameters are tuned through the GA to control the intermittent generation of RESs [36]. The PID controller controls energy per unit prices (p) to establish balance between power generation and consumption. Whereas a renewable energy integrated microgrid scenario shows that consumers' demand can be settled through STSMC, which adjust the per unit energy price to the DSLM of grid community. Closed-loop STSMC is used to control the undetermined and variable load for maintaining the energy balance. The dynamic price of energy is a key factor to manage the load on consumers' side. As the demand is elastic due to intermittent sources and the automated application in smart grid can easily determine and regulate. The fractional-order PI controller is employing for energy production control by dynamic price in closed loop system. To make the multi-source generation more realistic and stable the uncertainty is added in it. It is cleared by the simulations output that fractional order integrator (l) can be useful for decreasing the average energy deficiency error and price volatility in the smart grid energy markets [13]. Our proposed adaptive PSO-STSMC technique offers benefits of enhancing electricity per unit price reaction of control system when compared with PI and PID controller's response. Moreover, there are various applications of the STSMC control technique in industries and removing steady state error in nonlinear systems, which are presented in the works [37]–[40].

In optimization, the points where conditions are the best and most favourable are said to be optimum points. We do the optimization to find the best among different possible solution. In order to ensure optimization of the parameters of the STSMC, it is mandatory to keep in mind the limits of local optimal solution. Whereas, in the heuristic algorithms, the fall into local optimal solution cannot be ignored. Also, these algorithms are based on greedy strategy and essentially miss better optimal solutions which are not existed in the greedy rule [41]. Eventually when the local optimal solution is derived, various other heuristic algorithms also find the global optimal solution in given optimization problem. Whereas, the choosing of the optimization technique purely depends upon the performance in solving that optimization problem. Hence, an optimization algorithm can be chosen based on the optimization and solving solution time, hence algorithms with fastest optimization speed are preferred. Moreover, authors in [42], [43] demonstrated through comparing various algorithms with PSO algorithm in terms of the convergence speed, where the PSO algorithm has the

TABLE 2. Summary of related work in terms of methodology, objectives, results and shortcomings.

Ref.	Methodology	Objectives	Results	Limitations
[49]	Piece wise linear price demand modeling	Analysis of Demand elasticity	Selections of two extreme points for getting the correct price demand relation	Exact and uncertain factors affect the local market demand and price data
[50]	Genetic WDO (GWDO) algorithm, hybrid of GA and WDO	Load balancing through load scheduling	GWDO technique best performs in terms of electricity cost and PAR reduction than its counterparts	Enhance the reliability of the power system
[52]	Itching between time shifting and amplitude modulation load mode	Demand side management of household appliances	Comparison of results is presented for summer and winter seasons	CO_2 emission coming from the diesel generator functioning
[53]	Real-time residential TOU pricing solution using closed-loop consumer feedback is proposed	To boost the social welfare by reducing the cost of energy for utility and consumer	Proposed approach can be powerful solution for RT price-based demand response program	The individual household electricity demand is recorded by a smart meter not of all community
[54]	Conventional three-phase local power supply system	Combination of renewable generation in hybrid DC/AC microgrids	Grid energy and local DG energy can continuously support each other	The energy conversion station can handle the faults in grid lines
[55]	Instantaneous changing of solar, wind, and load demand	evaluation of "best-fit" participation factors (PFs)	Approach is same as that in the conventional approach	Applicable only for two renewable energy sources solar and wind
[56]	Stochastic model	Demand response scheduling	DR program reserve does not impose computational problem to the stochastic model	Only two test systems to describe the benefit
[57]	Game formulations for proposed real-time pricing	Demand-side management	Prices for opportunistic users offered by wholesaler	The best response is bounded to specific numbers of users
[58]	General economic equilibrium model	Net transformation of our energy systems	Extreme price volatility	Lack of small level equilibrium analysis
[59]	RES-E support systems are financed through the electricity market	The electricity prices in the European Union	Electricity prices increase due to RES-E, greenhouse gas and country's characteristics	Disputation about the final effect of RES-E on household electricity prices
[61]	Dynamic power system model	Future energy planning	Isolated mode of operation of the Danish island of Bornholm	Less energy is utilized than planned energy
[62]	Energy plan tool based on the year 2007	Wind power is integrated on large-scale	26 is the maximum attainable wind power penetration level	Difference was 1.41 percent within natural gas usage
[63]	Front-end calculation to calculate the energy generated	Optimization of a wind photovoltaic integrated hybrid system	Analysis for optimizing the size of the integrated system	Specific location and apply an iterative scheme

faster convergence speed and that too in the early stage of the solving the optimization problem. With the capability of larger coefficients of acceleration, and large speed setting in the PSO algorithm, it is more obvious to find the global optimal solution in less computational time. Whereas with the same capability of the PSO algorithm makes it to not fall

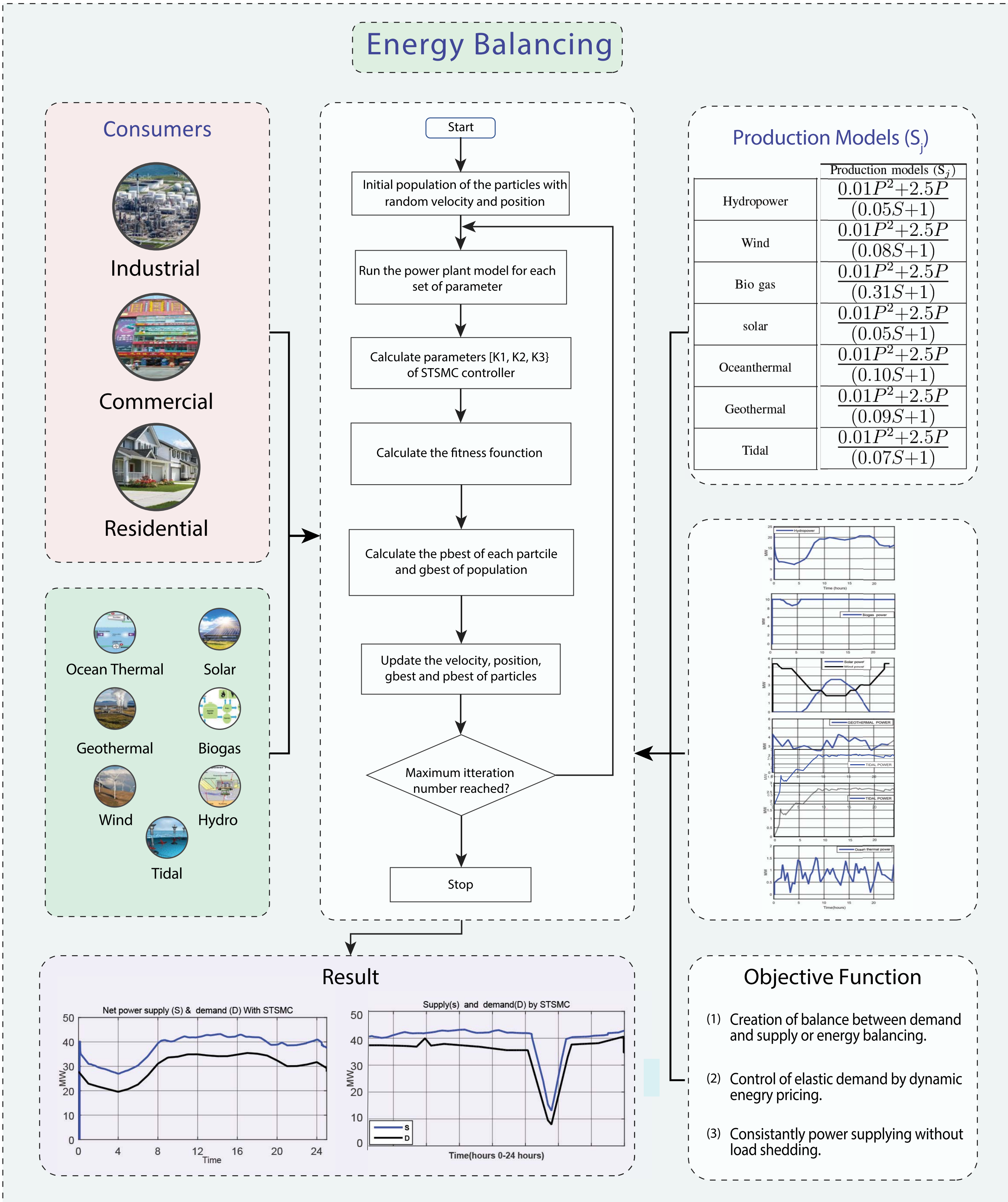

FIGURE 1. Over all implementation flow chart of the proposed energy balancing model with seven renewable energy sources for the consumption areas of residential, commercial and industrial in smart microgrid.

or stuck in local optimal solution. Hence, an algorithm should be constrained to ensure finding the global optimal solution to the optimization problem. Also, authors in [44], [45] carried out a PSO based optimization problem solving technique, and concluded that the for continuous value optimization problems, PSO algorithm has a memory function and moves toward the global and local optimal solution in each iteration of the optimization algorithm. Hence, by properly limiting the range for the STSMC controller's coefficients values, and settling the PSO parameters will result in faster convergence towards the global optimal solution without being stuck in the local optimal solution. So, in the case of the closed loop energy market management using dynamic pricing, the PSO algorithm is used to optimize the STSMC coefficients, which eventually finds the global optimal solution of the algorithm and greatly shorten the optimization time.

The particle swarm optimization (PSO) algorithm is initialized with random number of birds. Each member is called particle and the population is swarm. Each particle is seeks the optimum value by updating generation (iteration). In each iteration every particle is upgraded by the two best values. First one is the fitness value or the best solution. Second best one is tracked by particle swarm optimizer. They are flying towards the location of the best fitness of particle itself and by the location of whole population (global version of the algorithm) [46]. The STSMC algorithm is applied to decrease the uncertainty of the linear plants to find the robustness, and STSMC $u(t)$ was used in [47] for removing mismatch between generation and demand, which is modeled as follows:

$$C_{STSMC}(t) = k_1 e + k_2\sqrt{(|e|)}sign(e) + v \tag{1}$$

$$v = k_3 sign(e) \tag{2}$$

where, e is error obtained by comparison of demand and supply, k_1, k_2, k_3 are the parameters of the STSMC and sign is a function used to decrease the chattering or noise effects in STSMC. These parameters are tuned to get optimal results. STSMC has 3 coefficients; k_1 is the proportionality constant, The range of k_2 is between [0 1] and k_3 is the integral constant [48]. The proposed model is PSO-STSMC that tuned the parameters, k_1, k_2, k_3 multiple times and gives the best optimized parameters. These parameters are the most suitable for adjusting the fluctuating energy generation, so that it follows the demand of consumers. Hence, PSO-STSMC plays a vital role for energy balancing process.

V. CLOSED-LOOP ENERGY MARKET MANAGEMENT MODEL

The energy is one of the major requirement of daily life and has become the wheel of running modern industrial development. The energy is demanded by different areas of the community like industrial, commercial and residential. The demanded energy is not the same by all consumer's sides, high amount of energy is required to industry and then to commercial markets and residential areas respectively. so, there is flexibility in demand and it does not remain constant.

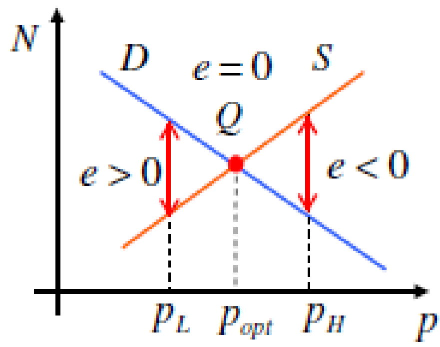

FIGURE 2. Demand and generation elasticity curve 1,2.

The unbalancing situation may also occur due to high demand of energy consumers comparatively with low generation and its vice versa. The overall modelling of the market scenario and price based energy management system is carried-out in [13], [14], and mathematically defined using the following equations.

$$e = D - S \tag{3}$$

The scenario is developed to diminish the D and S difference in close loop PID controller and the error is tackled by applying the mentioned technique Figure 4. In closed loop system the desired response or input and output response are compared at summing junction, if there is any error (e) the controller drives the plant to make the correction. PID controller decreases the steady state error and enhances the system's performance by increasing forward path gain, minimizes fluctuation, contains small offsets and can control the process with rapidly changing output. The error becomes zero when D and S are equal, which is shown in equations (4) and (5) [13], [14].

$$D = S \tag{4}$$

$$e = 0 \tag{5}$$

If demand is greater than supply $D > S$ then error is positive $e > 0$ and in case demand is smaller than supply $D < S$ the error will be negative $e < 0$ At point Q, D and S are equal and both are the function of price (p) which is presented in [13], [14]. For liberal market it is the best price for consumers. At Q point demand and supply curves intersect one another and provide the optimal market price as shown in Figure 2.

$$D(p) = S(p) \tag{6}$$

The analytical model is used to show the energy suppliers where the energy production capacity is determined by the polynomial (p) of energy price. The below represented energy production model is applied to show the price response of energy supplying companies taken from [13], [14].

$$s_d(p) = \sum_{i=0}^{d} a_i p^i \tag{7}$$

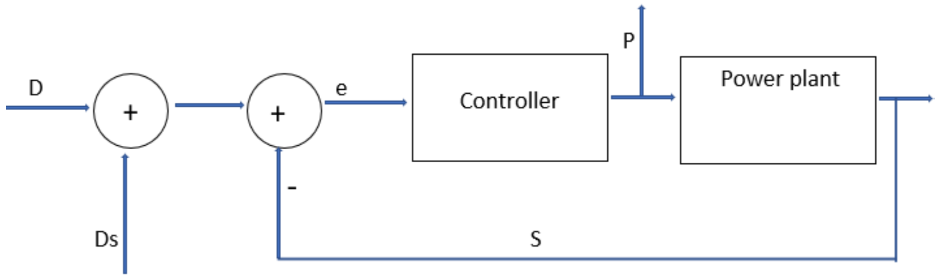

FIGURE 3. Block diagram of closed-loop supply control by dynamic pricing.

TABLE 3. Model parameters used in simulation scenario of 50MW installed power.

Energy source	Percentage contribution	Cmax(MW)	T(min)	Po,j(cent/kWh)
Hydro power	40	20	5	8.2
Solar	8	4	5	22
Bio gas	20	10	30	4.15
Wind	12	6	8	5
Ocean thermal	4	2	10	6
Geothermal	10	5	9	8
Tidal	6	3	7	10

Here d is the degree of the polynomial. It is cleared from Figure 2 that with the increase in energy per unit price, energy production is also increased and suppliers will get the opportunity to get more profit by selling the energy to the grid consumers as discussed in [13], [14]. Energy production delay and price broadcasting delay from suppliers is also used for energy generation modelling. The product of $s_d(p)$ with $\frac{1}{(\tau s+1)}$ gives the production delay model of energy. Where $\frac{1}{(\tau s+1)}$ is a transfer function and time constant is denoted by τ. The below mentioned transfer function depends on per unit price of energy [13], [14].

$$S_j = S_d(p)\frac{1}{\tau s + 1} \tag{8}$$

There is another important parameters of virtual demand is added in the actual demand, which is modeled as follows [13], [14].

$$e = D + D_s - S \tag{9}$$

As a result of D_s the generated energy is greater than the actual demand. It sets a margin by which energy shortage can be avoided because persistent energy shortage cause power outage [15].

In proposed system model, the generation sources considered are renewable energy resources the output of which depends on the solar irradiance, environmental and weather conditions Figure 8. The energy generated by them is fluctuating. In the intermittent conditions energy supplier companies have to fulfill the demand of customers according to the generation. The power is supplied from the local grid station of renewable energy. To cope up the high consumption of electricity, the operator of distribution system provides DR programs. The proposed STSMC is used due to its high robustness, stability and accuracy features. The applied STSMC controller reduces the error and the intermittent supply follows the demand in the best suitable way. Our focus will be on dynamic energy price which is the price-based demand response programs. Energy is provided to consumers in real-time even there is a high or low change in demand. Therefore, automation of load manage structures is an essential factor for demand side electricity management. Smart electricity systems are developed for the management of elastic demand of consumers using PSO-STSMC by dynamic price server as shown in Figure 7. D and S data is communicated with dynamic price generation server. If there is any gap (e) between S and D, it is minimized by STSMC, then price signal is sent to consumers through dynamic price server. The dynamic price is shown on smart meter through which consumers can alter their demand. Other strategies along this are load moving and load shifting for energy management [64].

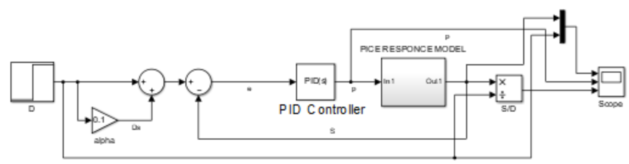

FIGURE 4. Response of PID controllers for unit step reference signal.

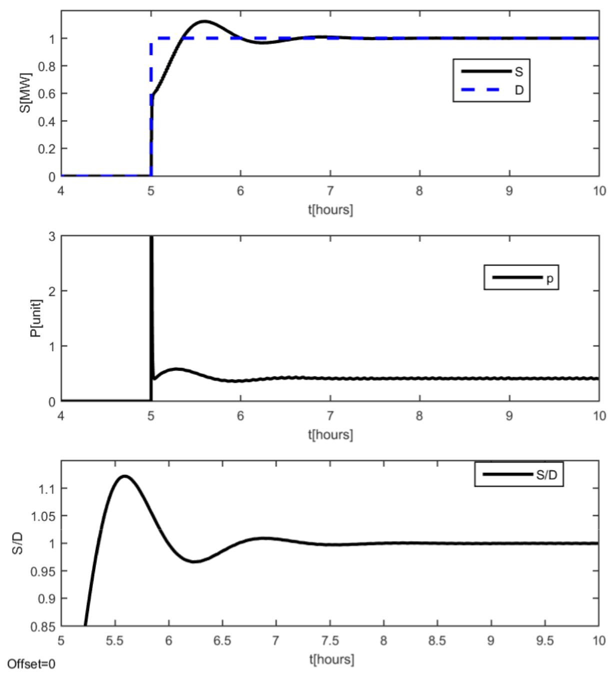

FIGURE 5. PID controller response for the input step demand signal at hour 5 in the price response model of $\frac{0.01P^2+2.5P}{(0.4S+1)}$ with $\alpha = 0, k_p = 1, k_i = 10, k_d = 0.2$.

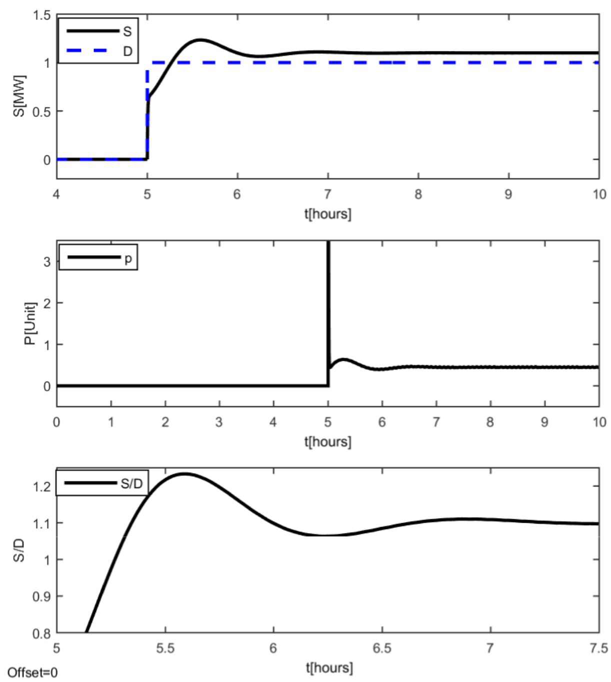

FIGURE 6. Response of PID controller to a step demand created at hour 5 in an energy supplier price response model of $\frac{0.01P^2+2.5P}{(0.4S+1)}$ with $\alpha = 0.1, k_p = 1, k_i = 10, k_d = 0.2$.

VI. SIMULATION RESULTS AND PERFORMANCE EVALUATIONS

This section describes the simulation scenario of multi renewable energy source model in smart micro grid (SG).

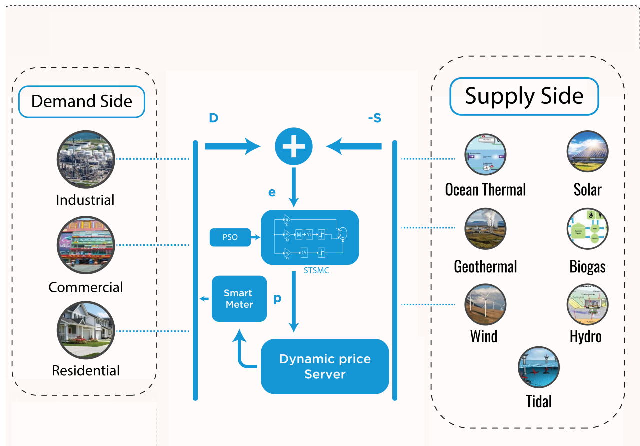

FIGURE 7. Schematic diagram for demand side energy management in smart microgrid.

The proposed model contains diverse sources like hydro power, wind, tidal, bio gas, geothermal, and solar power. The numerical values for the solar, hydro power, wind, and tidal are taken from the study of [14]. The major challenges for balancing D and S are occur because of wind and solar renewable power sources, as they have fluctuating generation characteristics Figure 9.

Simulation results are categorized into two sections, first one is the description of results without optimization and the second one explains the optimized techniques' performance.

A. SCENARIO 1: RESPONSE OF MULTI POWER GENERATION MODEL WITHOUT OPTIMIZATION USING DIFFERENT CONTROLLERS FOR THE DEMAND OF CONSUMERS

Simulation results of multi renewable energy sources that generates 50MW power using PD, FO-PD, PI, PID and STSMC controller applying individually in close loop system. P_c, S/D and their comparative analysis are explained in detail.

1) MULTI SOURCE POWER GENERATION MODEL OF 50MW USING DIFFERENT CONTROLLERS

The overall energy production (S_T) is defined as the sum of the production from all energy sources.

$$S_T = \sum_{J=1}^{m} G_j \tag{10}$$

where m represents that the how many energy sources are there and G_j is the net production of energy through jth energy source. The energy production model can be made more consistent and persistent by following two factors. Energy suppliers must earn their benefit and initiate to provide to smart grid when the price of energy is higher than the production costs. Second, each energy source has installed maximum capacity C_{max} that limits the power generation. By the help of above factors, the below models explains the energy production

TABLE 4. Renewable energy generation model.

j	Energy source type	T(min)	$\tau_j(h)$	Production models (S_j)
1	Hydro power	5	0.05	$\frac{0.01P^2+2.5P}{(0.05S+1)}$
2	Wind	8	0.08	$\frac{0.01P^2+2.5P}{(0.08S+1)}$
3	Bio gas	30	0.31	$\frac{0.01P^2+2.5P}{(0.31S+1)}$
4	solar	5	0.05	$\frac{0.01P^2+2.5P}{(0.05S+1)}$
5	Ocean thermal	10	0.10	$\frac{0.01P^2+2.5P}{(0.10S+1)}$
6	Geothermal	9	0.09	$\frac{0.01P^2+2.5P}{(0.09S+1)}$
7	Tidal	7	0.07	$\frac{0.01P^2+2.5P}{(0.07S+1)}$

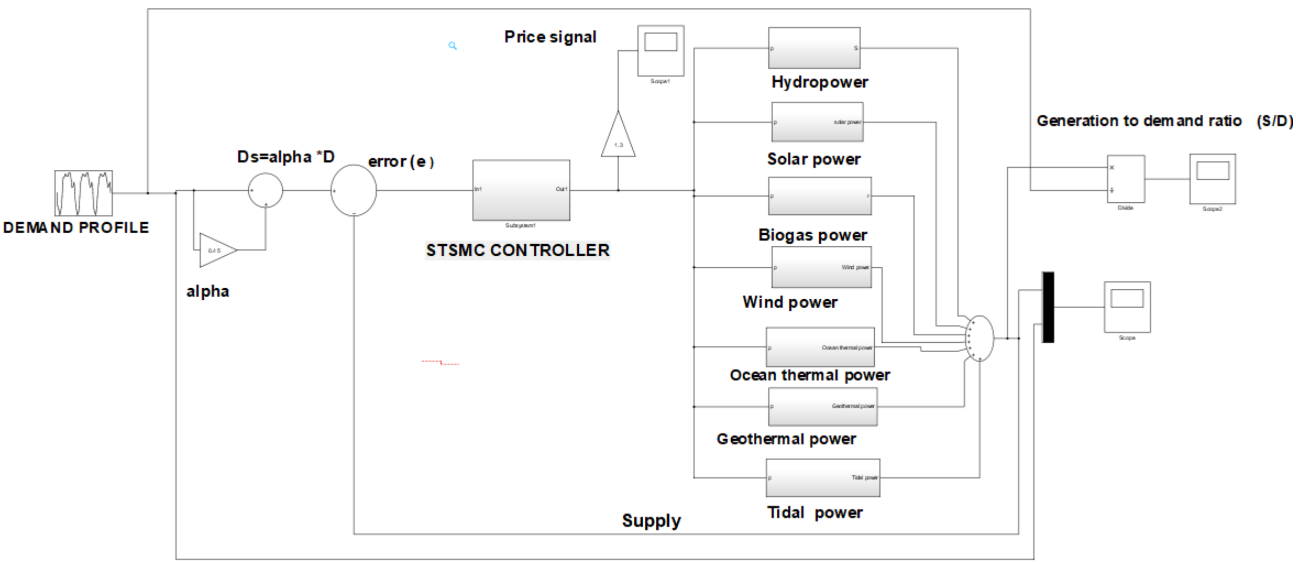

FIGURE 8. Multi power generation model installed for 50 MW.

price function of the jth renewable source:

$$G_j = \begin{cases} 0 & p < p_{0,j} \\ S_j & p_{0,j} \leq pVS_j \leq C_{max,j} \\ C_{max,j} & S_j > C_{max,j} \end{cases} \quad (11)$$

The average cost of energy is represented by $p_{0,j}$ for jth source type. The production model is S_j for the jth source type according to Equation 8. The time constant S_j for a capacitive system can be calculated using the following formula by putting the value of T_j.

$$\tau_j = (1 - e^{-}1)Tj \quad (12)$$

The production models are developed for every power source by the Equation 7 and Equation 8 and by entering the values of τ_j from Table 4. Figure 8 shows the multi power generation model that is installed for 50MW. The power generation consistently follows the demand as a result energy balance in the market remain stable. In order to avoid the power outage virtual demand is added to actual demand by

$$\frac{S}{D} = 1.5 \quad (13)$$

From Figure 10, it is clear that this ratio is altering from 1.2 to 1.5 that is enough to tackle emergent conditions of powers. The controller coefficients are taken from [15]. In case of FO-PD, kp = 1, ki = 10, kd = 0.2 and λ = 0.33 coefficients values are used in each technique as per requirement.

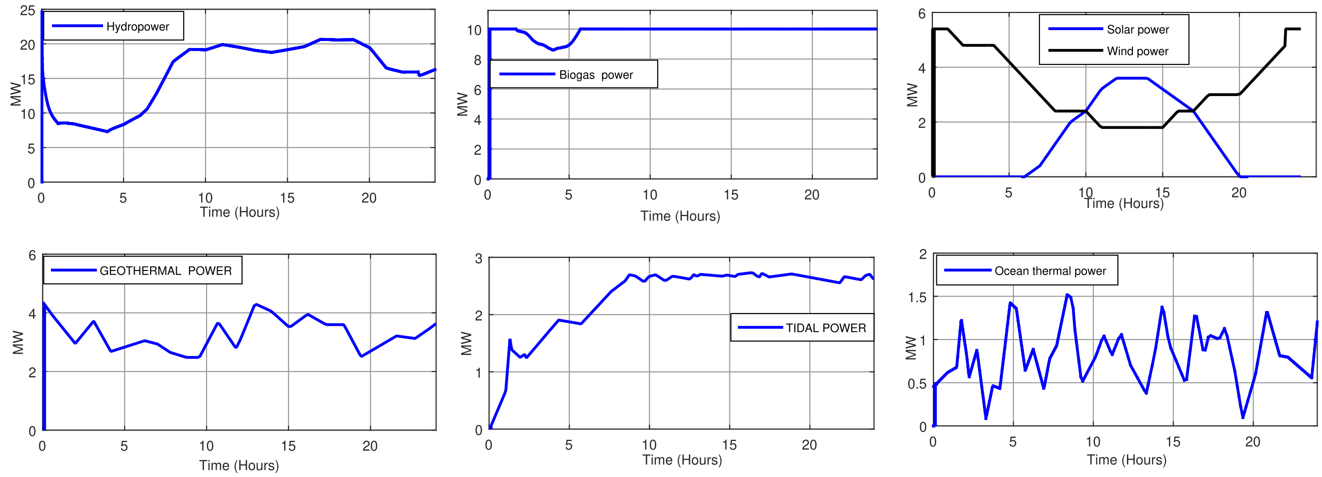

FIGURE 9. Energy generated by renewable sources.

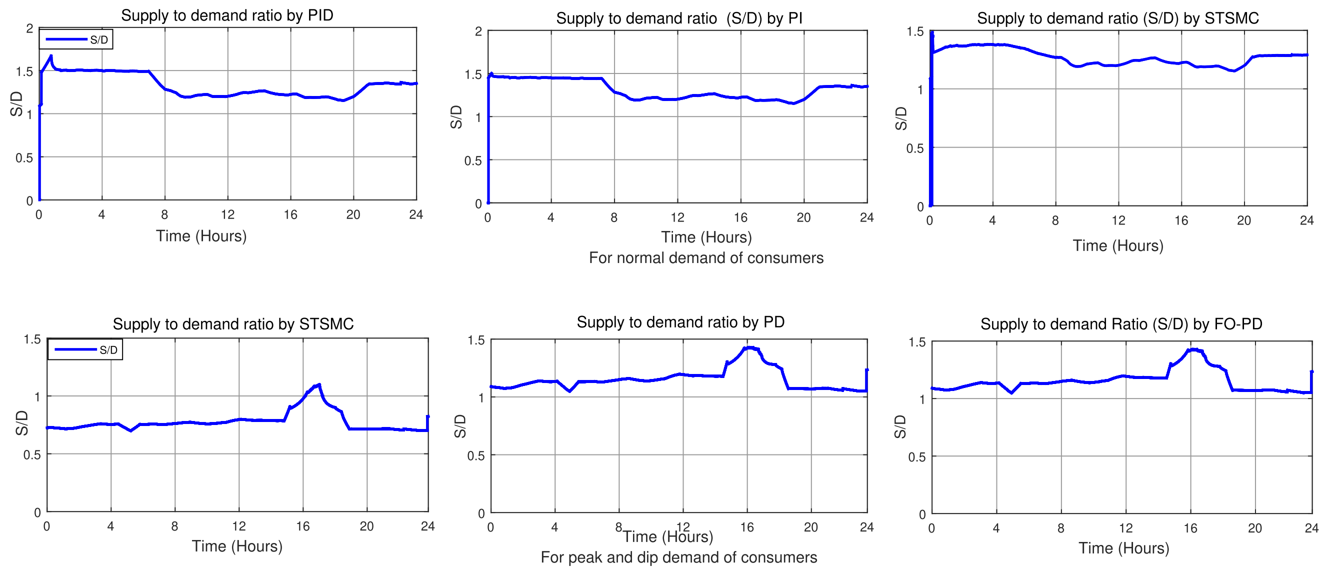

FIGURE 10. Supply to demand ratio (S/D) of multi power generation model for normal as well as peak and dip demand without optimization.

2) PROCESS OF ENERGY BALANCING

The major processes involved in biogas energy generations are; bio, thermo and physico-chemical conversion. It is complex to initiate and manage such long step process. As a result the response time of biogas energy source is 4-5 times greater than the response times of remaining sources of energy, its response to the price change is very slower than the others Figure 9. But, hydroelectric and tidal stations are quickly follow the change in energy price. The hydroelectricity stations has maximum installed capacity and follow the price change as well, so it can counter the change in energy requirements. Hence, hydroelectric station has key role in balancing demand and supply Figure 11. The wind, solar, ocean thermal and geothermal energy generation can respond to demand changes at the peak of their full instantaneous capacities, which depend up on the environmental, climate and sun light condition Table 3.

3) COMPARATIVE ANALYSIS OF APPLIED TECHNIQUES

It is assumed that when the energy price increases the energy supply companies get the better opportunities of earning required profit. From Figure 12 in case of PID and PI controller techniques, when demand is normal the price is zero to the customers till 8:00hour, this period will give loss to the companies and they will not be convinced to generate demanded power, after that, the price is gradually increasing even it cross the limit of 1800cent/kwh in PID technique and 1500cent/kwh in PI technique at 24:00hour. The grid consumers do not tolerate such high cost of energy. In technique STSMC the energy price will reach up to the 20cent/kwh, this price is totally according to the supplied power and not reaches to zero that cause the financial deficit to suppliers. The per unit price is not so enhanced that is out of the customer's financial approach. So, the best possible technique among PID, PI and

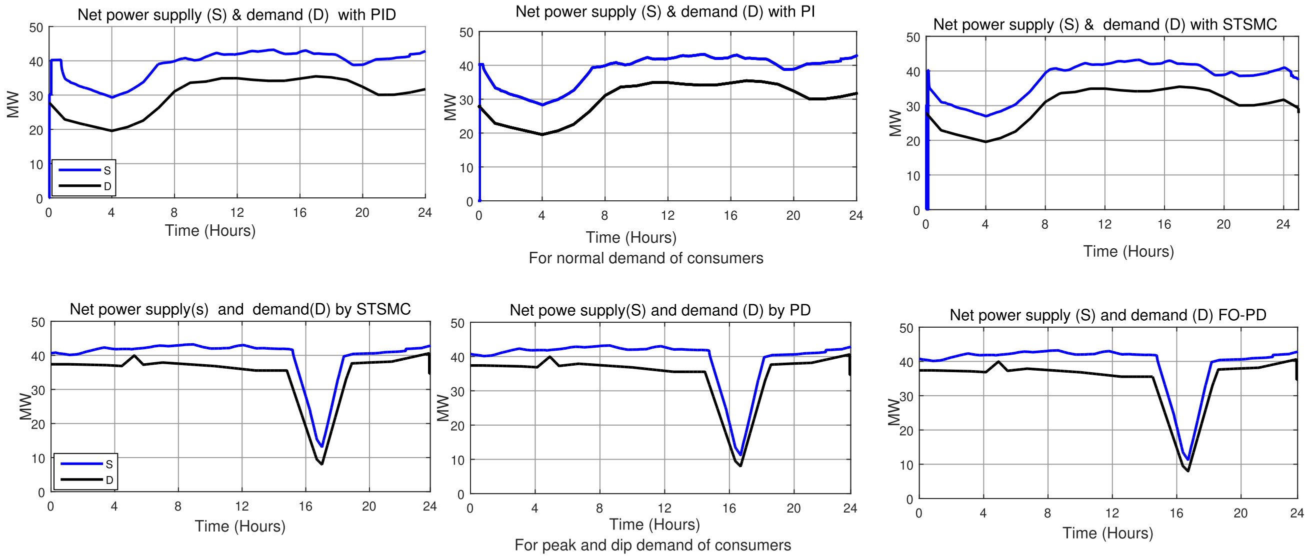

FIGURE 11. Response of multi power generation model for normal as well as peak and dip demand without optimization.

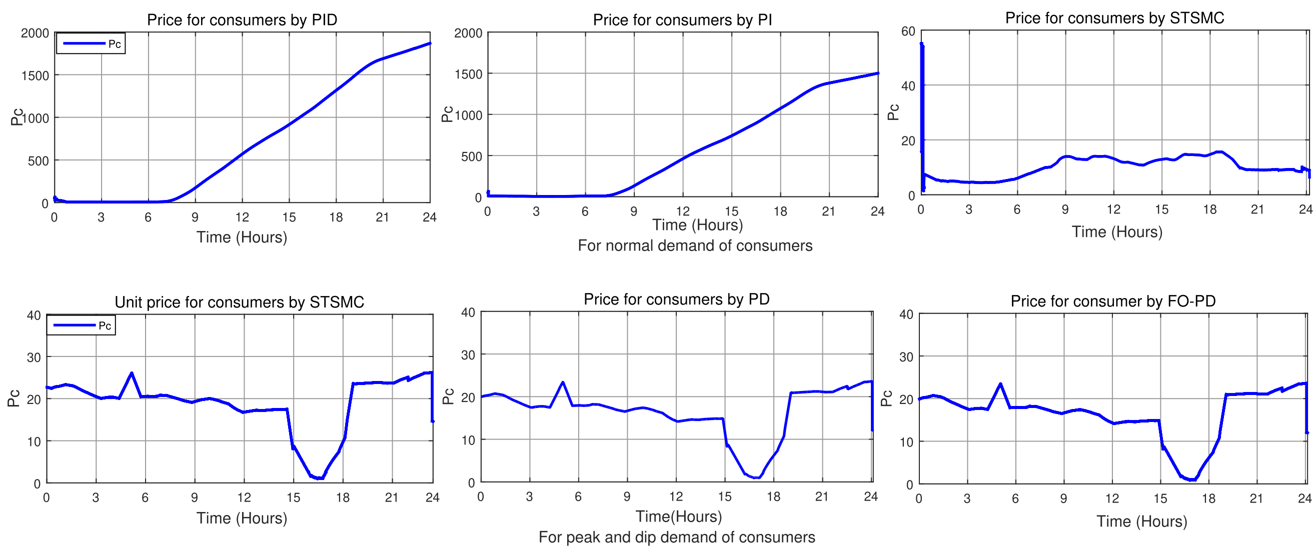

FIGURE 12. Price response of multi power generation model for normal as well as peak and dip demand without optimization.

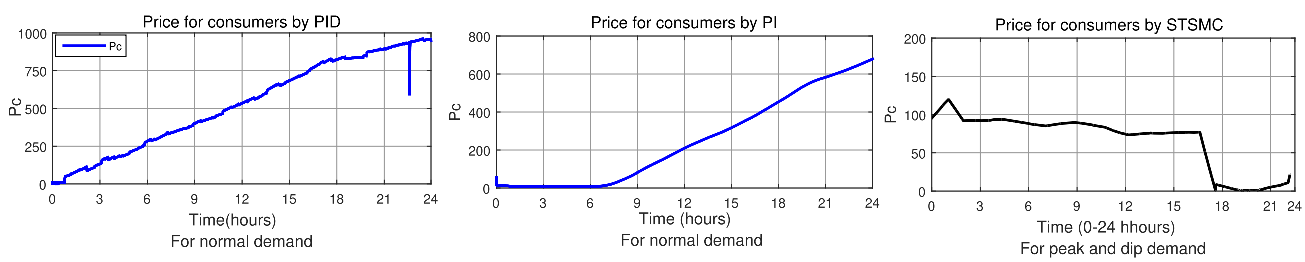

FIGURE 13. Price response of multi power generation model for normal as well as peak and dip demand with optimization.

STSMC which is beneficial both for suppliers and customers is STSMC.

In case of peak and dip demand Figure 12 three techniques are applied STSMC, PD and FO-PD. The price is maximum and minimum at peak and dip hours respectively so, the consumers will pay the price according to their energy usage in all mentioned techniques. Along with this, only the STSMC technique is useful for energy companies to earn so much

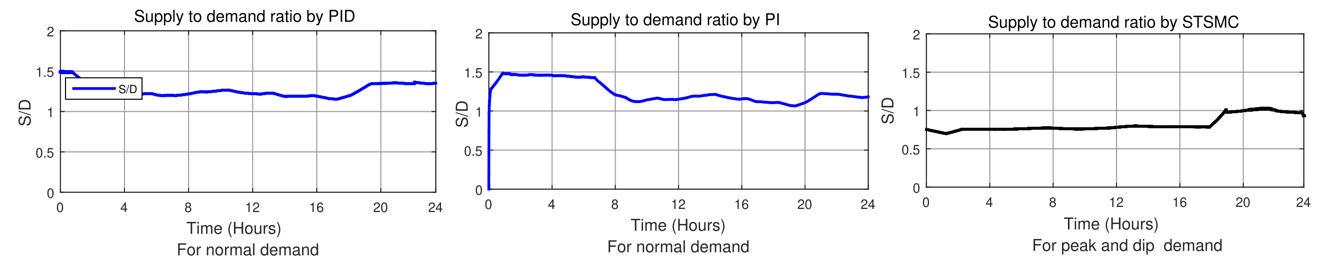

FIGURE 14. Supply to demand ratio (S/D) of multi power generation model for normal as well as peak and dip demand with optimization.

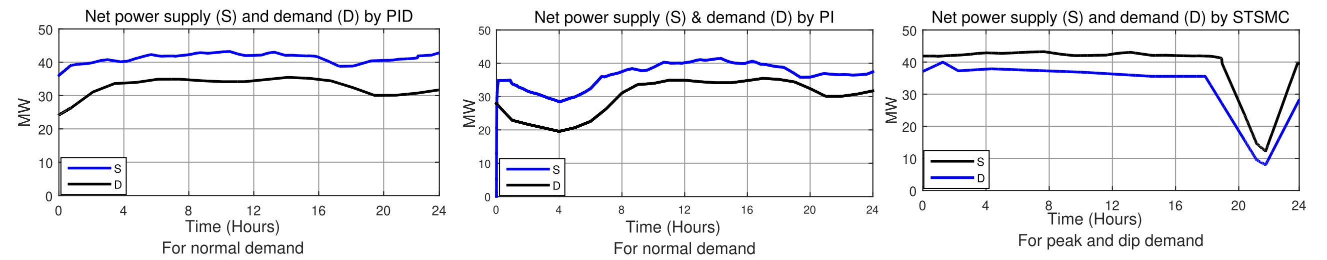

FIGURE 15. Response of multi power generation model for normal as well as peak and dip demand with optimization.

TABLE 5. Optimized gains and rise time, settling time, percentage overshoot.

Controller	Rise time (s)	Settling time (s)	Percent overshoot	k_p	k_i	k_d
DE-PI	0.278	0.735	14.2	2.09	3.46	-
DE-PID	0.257	0.863	11.3	1.54	7.87	3.89
DE-STSMC	0.236	0.849	10.7	K1=7.341	K2=0.001	K3=7.178
GA-PI	0.266	0.857	11.37	4.13	3.45	-
GA-PID	0.236	0.839	10.89	5.41	8.7	6.178
GA-STSMC	0.249	0.824	9.7	K1=3.827	K2=0.001	K3=3.1245
PSO-PI	0.214	0.779	13.7	1.0609	3.1245	-
PSO-PID	0.229	0.809	7.93	0.3854	9.3787	5.934
PSO-STSMC	0.201	0.780	6.54	K1= 10.8943	K2=0.0877	K3=12.9462

amount that is profitable and fulfill the expenditures of the energy production. This technique is better for suppliers and consumer than the PD and FO-PD.

B. SCENARIO 2: RESPONSE OF MULTI POWER GENERATION MODEL WITH OPTIMIZATION USING DIFFERENT CONTROLLERS FOR THE DEMAND OF CONSUMERS

Similarly, among optimized techniques, in PSO-STSMC the per unit price is not so high or low and it is suitable both for suppliers and consumers Figure 13. PSO-STSMC is better in performance than PSO-PID and PSO-PI. Since there is a direct relationship between price and supply, when the price increases, the supply increases in the market. In PSO-STSMC at peak demand the time of 2:00hour the price is 130cent/kWh and at the time of 22:00hours when demand is minimum the price is 1cent/kWh and throughout 24:00hours the price by PSO-STSMC is greater than STSMC.

This analysis shows that if we compare PSO-STSMC response to the benchmark controllers' response as givem in Table. 5 shows better output because it convinces the suppliers to generate high amount of energy for getting the acceptable profit. This due to the robustness of the PSO-STSMC controller which quickly started tracing the demand, and provides lower energy price both for the consumers and suppliers. Moreover, due to the robustness of the PSO-STSMC control technique, the rise time, settling time, and overshoot are also less when compared with the PID and PI based control approach. Hence, PSO-STSMC has a key role to control the demand side load and thus creates energy balance as shown in Figure15. So, it is cleared that from without optimized and optimized techniques the outstanding performance is of our proposed model of PSO-STSMC.

Gain tuning of PID, PI and STSMC controllers' coefficients is performed by DE, GA, and PSO optimization as mentioned in the Table 5. The best optimum gains are obtained through them, performance of PSO-STSMC is far better than other optimized results. There is low percentage overshoot of 6.54 of PSO-STSMC which means it can earlier achieve the target of reducing the error. The settling time of PSO-STSMC is 0.780hours which means the systems will have to face less number oscillations and it can be stable in shorter time. Lower rise time of PSO-STSMC is another important parameter that show preference of our proposed system technique as compared to GA-PI, GA-PID, GA-STSMC, DE-PI, DE-PID, DE-STSMC, PSO-PID, and PSO-PI.

VII. CONCLUSION

This study illustrates that elastic demand can be controlled and made highly reliable without uncertain conditions by the application of DSLM that operates automatically. It is described that dynamic price is the preferable solution for the demand side load control. The simulation results showed that price control by STSMC is a self-governing technique to handle the instantaneous, normal and sharp demand variations in multi-source power of energy market. It is observed from the simulations that renewable energy integrated microgrid generation by PSO-STSMC can express the magnificent performance of tracing the price-based elastic demand in a closed loop energy market price management. Our findings show that through PSO-STSMC, generation traces the demand, even when the demand is at peak value of 40MW at 2:00hours or minimum value of of 9MW at 22:00hours. At peak and dip demand of 40MW and 9MW the generated powers by renewable distributed microgrid are 42MW and 11MW respectively. In PSO-STSMC the price increases and energy supplied by the sellers is also increased as they get the better chance of earning profit and when price of per unit energy is decreased the energy supply will be reduced. Maximum energy of 1008000kWh is supplied at the peak time of 2:00hour and the price is 130cent/kWh and minimum energy 216000kWh is supplied at 22:00hour and the price is 1cent/kWh. In case of PSO-PID and PSO-PI the prices are 1000cent/kWh and 630cent/kWh respectively. Such energy generation is so costly that it can not be paid by consumers, as a result the demand of energy will be reduced. It is shown in Table 5 that optimized gains of PSO-STSMC are achieved that play a vital to distinct it than others in terms of rise time, settling time and percentage overshoot. Through these parameters our system becomes more stable with the least steady state error. So, our proposed method of PSO-STSMC is better in performance than classical controller of PSO-PID and PSO-PI. PSO-STSMC plays a key role for the economically benefits of energy suppliers and consumers as well as for balancing of energy.

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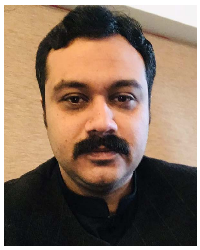

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