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ORIGINAL ARTICLE

Design of Supervisory Predictive Control for Fresh Water Production from Alternate Energy Sources

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ABSTRACT
Through this work we design and developed supervisory control system (SCS) with the help of model predictive control (MPC) to get the optimal operation and management of integrated wind-solar-sea wave energy system and reverse osmosis (RO) water desalination system unit. The MPC was designed in a way so that it can coordinate the energy generating units, i.e. the wind, solar, the sea wave energy systems and RO system. In the MPC design the advantage of two-time scale property of dynamics of integrated system has been taken. The design was done in such a way so that energy generation is maximum, energy saving is maximum, energy supply to the load is satisfactory, in one word the system operates with maximum optimality. It is also considered so that fulfilling the load demand the excess energy can be supplied to the grid system. The entire system is completely based on renewable energy sources, so there will be no pollution in any form. Simulation design is done in a 24-hour window with 1-hour deviation to check the applicability and the effectiveness of the system in real scenario.
Keywords: *Model based control, Wave power, Renewable energy, Desalination, Wave energy converter, Reverse osmosis, Supervisory predictive control (SPC)*

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INTRODUCTION

In power sector renewable energy technologies like wind, solar, sea wave, tidal energy are rising in demand significantly now a days because of its various advantages, like no pollution/ environment friendly, relevant to the situation and environment, easily accessible even in remote areas (depends on place and type of resource), it utilizes natural renewable sources, so never ending resource, though installation is costly, but once its installed then the operating cost is very low, promotes fuel diversification and energy autonomy. And the dwindling of fossil fuel reserves also a major reason to move to renewable energy sources. The other part of the system, i.e. RO method of water desalination, is efficient and advance process in compare to other available methods. Though these processes are very advance, it requires proper maintenance of desired process condition to operate the system optimally and successfully. The major problem with these three energy sources is all of them are very uncertain. Sudden rise and downfall of any or multiple parameters is very common in these systems. So for smooth operation a solution is needed to make the system enable to deal with the uncertainty, making the process smooth and providing a desired output even in case of sudden shortfall or rise of multiple energy sources. Integration of the entire system is one of the best solutions in this case. Now integration of such systems is very complex as voltage and current profile of different energy source unit is different in general and also they are varying in nature. However there are several methods available to make the system integration. Model Predictive Control approach is one of the best method to do the required system integration and very much relevant and convenient also in this case. As renewable energy technology is significantly rising in demand, several studies also being coming out to find the most reliable and efficient technology. The multi-pronged process-optimization approach for reverse osmosis desalination of water has high efficiency on membrane type water RO system [1]. There is also other study which focuses on sea water desalination [17]. Countries like Middle East, Greece, Spain, and Southern Europe in general and North Africa are having less access to drinkable or usable water, in other side these countries have access to the ocean water by using efficient desalination process. In worldwide 0.5- 1% is fresh water is available for plant, animal and human. Globally 97% water present in ocean as saline water and 2-2.5% is present in ice form. The World Health Organization (WHO) has set international guidelines for drinking water. Almost all countries have drinking water quality regulations, often inspired by WHO guidelines. According to the United Nations, over 1.1 billion people are currently without safe drinking water. More than half of the world's hospital beds are occupied by patients suffering from water borne diseases. Water borne diseases can be prevented by providing safe drinking water [18]. Another relevant study [19] shows on process on sea water and blackish water desalination to make drinkable water. After reviewing all these studies we found that the membrane type water reverse osmosis process is the most efficient and cost effective and most suitable for various purposes. Solar, sea wave, wind energy systems are new and few studies focused on the system behavior with integrated wind, solar system and vernacular power system connected with electrical grid [20] [21]. Energy production drop or increase is one of the major issues for renewable energy sources; to resolve this issue quick start units are required.

Most of the studies have done on control of stand-alone wind [3] or solar systems [4] to produce fresh water from RO systems. Few studies recently proposed on nonlinear model-based control technique to control energy production changes and saline water feed variations [5].

However, the results obtained in [6] focused on short-term system operation and the approach adopted there cannot be extended to long-term operation because of the high computational burden involved in solving the full, integrated system nonlinear dynamic model. The present study focused on the design of SCS for the optimal operation and management of integrated solar, wind, wave energy generation and RO system. The present study also focused on design the SCS via MPC to find optimality considerations and to handle the state and input constraints [7]. The MPC coordinates the wind, wave and solar units and battery bank to supply required energy to the RO unit to satisfy the overall water and storage demands. To reduce the computational demand of the MPC optimization problem, the advantages of two-time-scale property the integrated system adopted to simplify the control problem formulation. To illustrate the practical effectiveness and applicability multiple simulations have been carried out. There are other studies as well which is related to wind firms separately [23] it shows the response when connected to the grid. This work developed and demonstrated the technique of designing Maximum power point tracking (MPPT) for wind energy system. Finally, we evaluated MPC performance on future weather and water demand. We considered two cases such as: 1) only consider water demand for next hour and daily average fresh water requirement instead of the future 24-hr, 2) only consider weather forecast for next one hour and wind speed (daily average), insolation and PV cell average temperature (daytime and night).

MATERIAL AND METHODS

Integrated System Description

In this section the system is designed to have two operation modes: standalone operating mode and electrical grid-connected operating mode. The standalone operating mode provides necessary energy to RO unit from wind, solar, wave energy and the battery bank. In the grid-connected operating mode, the wave-wind-solar energy generation units and the battery bank supply energy to RO unit, and also send surplus energy to the electrical grid. Fig. 1 shows schematic of designed integrated wave, wind, solar, RO system.

Energy Generation System

Four energy generation subsystems such as wind, solar, wave and lead-acid battery bank are designed to supply energy for RO system. Windmill consist multipolar permanent-magnet synchronous generator (PMSG), rectifier, and DC/DC converter. The wave energy converter connected through a rectifier to the same DC/DC converter. The wind energy unit characterized by 3 nonlinear ordinary differential equations (ODEs) with quadrature current (i_q) and direct current (i_d) in the rotor reference frame and the angular speed (electrical) (ω_e). The wind electrical power generation is expressed as follows:

$$P_\omega = i_\omega v_b \qquad (1)$$

Where, $i_\omega = current\ injected\ to\ the\ DC\ bus\ by\ the\ wind = (\pi)/(2\sqrt{3})\sqrt{i_q^2 + i_d^2}\, u_\omega$, v_b = battery bank terminal voltage, and u_ω = control signal (duty cycle of the DC/DC converter).

Solar subsystem consist photo voltaic (PV) panel array and a DC/DC (half-bridge buck) converter which controls the operating limits of the PV panels. The solar generation subsystem characterized by 2 nonlinear ODEs linking the voltage reading on the PV array terminals (u_{pv}) and the current supplied into DC bus (i_s). Solar power supplied into DC bus calculated as follows:

$$P_s = i_s v_b \quad (2)$$

The battery bank is modeled as voltage source (E_b), which is in series with resistance (R_b) and capacitance (C_b). The DC bus voltage expressed as follows:

$$u_b = E_b + v_c + i_b R_b \quad (3)$$

Where, i_b= current across battery bank, v_c= voltage in capacitor, C_b=capacitance of the battery.
Voltage in capacitor is expressed as follows:

$$\dot{v_c} = \frac{1}{C_b} i_b \quad (4)$$

The state of charge (SOC) for the battery bank $S_b$can be calculated as follows:

$$s_b = \frac{Q_c}{Q_c^{max}} = \frac{V_c}{V_c^{max}} \quad (5)$$

Where, Q_c^{max} = maximum capacity of the capacitor corresponding to the maximum voltage (v_c^{max}) that can be tolerated by the capacitor. Depth of discharge of the battery bank (d_b) is calculated as follows:

$$d_b = 1 - s_b \quad (6)$$

The collected energy from wind, solar and wave deliver to the RO unit and surplus energy to battery bank and electrical grid through the DC bus. The DC bus voltage is determined by the battery bank. Binary variable (I_s) indicates the mode of operation of the integrated system. When,$I_s = 1$, the system is connected to the grid; and when, $I_s = 0$, the integrated system operates in standalone mode. Current balance equation for Ideal voltage inverter is expressed as follows:

$$i_\omega + i_s = I_{RO} + I_s i_G + i_b \quad (7)$$

Where, I_{RO}= currents supplied to the RO system and i_G = currents injected to electrical grid.

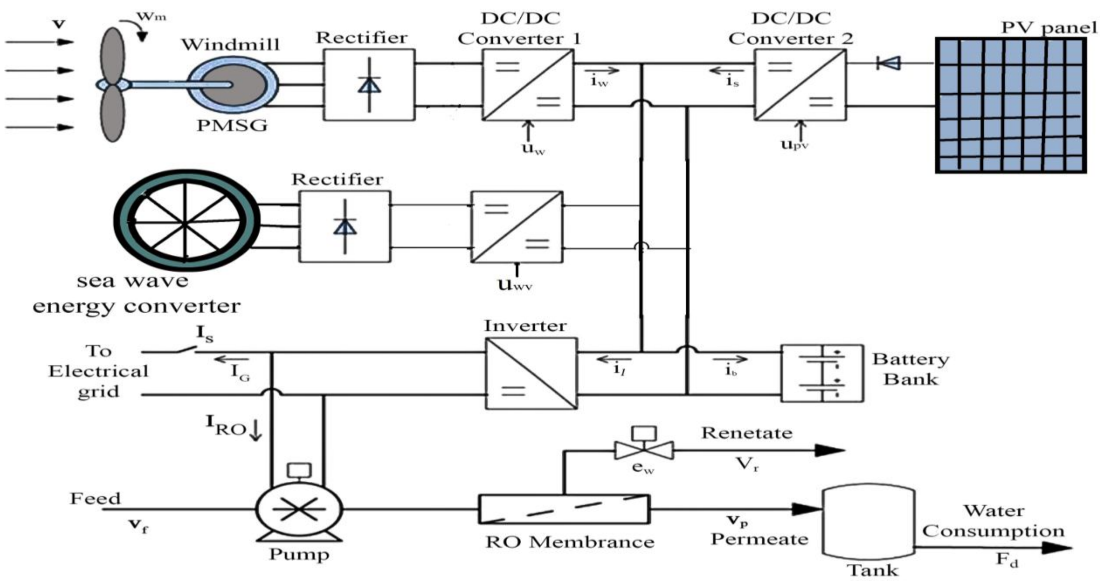

Fig.1. Integrated wind-solar-wave-RO system

Water Desalination System:

The RO water desalination system consists high-pressure pump, membrane module and water storage tank. The high-pressure pump pushes and pressurizes salt water to the feed pressure. Then, the membrane module separates the salt water into a relatively low-salinity (or permeate), and a high-salinity brine (or retentate) flow. The RO system considered as a mass balance and energy balance calculated around the actuated retentate valve, involving one ODE describing the retentate flow velocity (v_r).Various control techniques may be applied taking the valve resistance (e_{vr}) as the variable(manipulated) input. In this work, the RO system was operated at energy optimal water recovery(Y_{opt}), i.e. the ratio of the permeate flow velocity (v_p) to the feed flow velocity (v_f), is being adjusted in real time [1] [10]. Using Bernoulli equation (ignoring the water elevation change), power needed for the water desalination system can be expressed as follows:

$$P_{RO} = \frac{1}{\eta}\left(P_{sys}\frac{F_p}{Y_{opt}} + \frac{1}{2}\frac{F_p^3}{Y_{opt}^3 A_p^2}\rho_\omega\right),\ 0 < \eta < 1 \qquad (8)$$

Where, η = the overall power efficiency of the pump, P_{sys}=is the feed pressure, F_p= permeate flow rate (i.e., fresh water production rate to fulfill the water demands), A_p = pipe cross-sectional area, ρ_w = fluid density.

Let, F_d = water consumption demand and F_s = water storage demand, then we obtain the steady-state mass balance equation as follows:

$$0 = F_p - F_d - F_s \qquad (9)$$

Note that, F_s can take positive or negative values. With the help of Eq.(9), the status of the water level in the tank, h_l, can be expressed as:

$$h_l = \frac{F_s}{A_s} = \frac{A_p}{A_s}\left(v_f - v_r\right) - \frac{F_d}{A_s} \qquad (10)$$

Where, A_s = water storage tank cross-sectional area.

Similarly, the state of storage (SOS), $s_t$can be expressed as follows:

$$s_t = \frac{h_l}{h_l^{max}}$$

Where, h_l^{max} = maximum water level in the tank

Integrated Wind, Solar, wave, RO System:

The kinematics of the integrated wave, wind, solar, RO units can be written as:

$$\dot{x} = f(x) + g(x)u\ ; \qquad h(x) = 0\ ; \qquad (11)$$

Where, $x = (i_q i_d\,\omega_s v_{pv} i_s v_c v_r h_l)^T, u = [u_\omega\ u_{pv}\ e_{vr}]^T$ and f, g, h are nonlinear vector functions without explicit forms. We note that the dynamics of the integrated system exhibits a two-time-scale behavior. Specifically, the dynamics of the states $i_q\ i_d\ \omega_s\ v_{pv}\ i_s$ and v_r are relatively fast (in the order of seconds); and the dynamics of the states v_c and h_l are relatively slow (in the order of minutes).

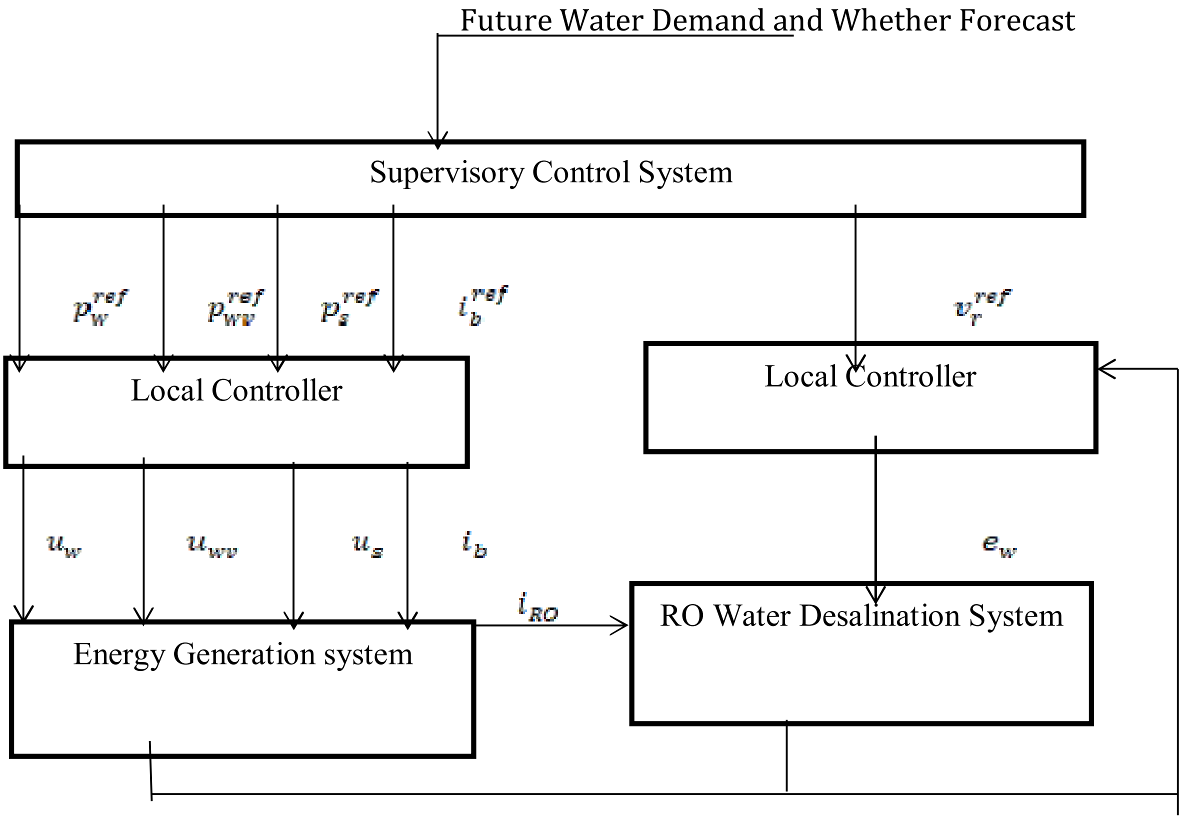

Fig. 2. Closed loop system of integrated Wind, Solar, wave, RO System

As per two-time-scale property, eq. 11has rewritten for the integrated system of **eq. 11** as follows:

$$\dot{x}_f = f_f(x_f, x_s) + g_f(x_f, x_s)u$$

$$\dot{x}_s = f_s(x_f, x_s)$$
$$h(x) = 0 \qquad (12)$$

Where, $f_s(x_f, x_s) = \begin{bmatrix} \frac{1}{c_b} i_b \\ \frac{A_p}{A_s}(u_f - u_r) - \frac{F_d}{A_s} \end{bmatrix}$ and $x_f = [i_q i_d \omega_e v_{pv} i_s v_r]^T$, $x_s = [v_c, h_l]^T$

The advantages of two-time-scale property used for formulation of the MPC (eq.12) with x_f=0

Formulation of Control System:

The supervisory control system (SCS) primarily designed to regulate the integrated energy to produce fresh water from RO water desalination system. Secondarily the supervisory control system optimally supplies electricity for the system operations, like battery maintenance and energy savings and supply of electricity to the electrical grid as well.

The trajectories hint the local controller which directs the subsystems to track the intimations of the operating trajectories. The schematic closed loop system of integrated Wind, Solar, wave, RO System is shown in Fig. 2.

Design of Local Controllers:

The windmill controller forces the windmill to track the intimations of the operating trajectories, which is the desired power generation (p_w^{ref}) computed by the SCS [11].

The solar subsystem controller forces the solar arrangement to track the intimations of the operating trajectory, i.e. the desired power generation (p_s^{ref}) computed by the SCS [9].

The local controller regulates the retentate valve resistance to follow the reference retentate flow velocity (v_r^{ref}) computed by SCS [5]. The SCS also sends a reference charge/ discharge current trajectory (i_b^{ref}) to the battery bank; however, the battery bank local controller doesn't follow this reference all the time. In standalone operating mode (i.e.- $i_s = 0$) no extra energy supply to electrical grid and for on-grid mode (i.e., $i_s = 1, i_g = 0$) supply current goes to battery bank, determined by the current balance. The local controller operates based on real-time measurements of i_w, i_s, i_{RO} and adopts the following control strategy [12]:

$$i_b = \begin{cases} i_w + i_s - i_{RO} & if\ i_s = 0 \\ min\{i_b^{ref}, i_w + i_s - i_{RO}\}, & if\ i_s = 1 \end{cases} \qquad (13)$$

Supervisory Predictive Controller Design

The objective of the SCS is to deter-mine the operating power references ($p_w^{ref}, p_{wv}^{ref}, p_s^{ref}$) for the wind, wave and solar subsystems, the reference retntate flow rate (v_r^{ref}) for the RO, and the charge/discharge current (i_b^{ref}) of battery bank. The SCS is designed via MPC as it can take into ac-count optimality considerations and handle state and input constraints [12], [13].

The RO subsystem has operated optimally (energy optimal water recovery(Y_{opt})) so that the energy consumption per unit fresh water production is minimalized [1].

In addition, it is assumed a preferred SOS, state of the storage tank (s_t^{opt}) is the balance water between the tank capacity and store extra water. We considered that future water consumption demands ($F_d(t)$) of the RO is known. We also considered hourly weather changes for this study. The MPC is assessed at discrete time instants $t_k = t_0 + k\Delta, k = 0, 1$ .... with the initial time (t_0) and the sampling time (Δ). For every sampling time, piece-wise constant trajectories for the different subsystems (i.e., $P_w^{ref}, P_s^{ref}, v_r^{ref}$ and i_b^{ref}) for a certain time period (prediction horizon) are obtained but only the first piece of the trajectories are directed to local controllers and rest trajectories are restricted. Specifically, the supervisory MPC cost functions are as follows:

$$j(t) = \alpha(1 - I_s)\int_0^{N\Delta}\left(p_{RO}(\tau) + i_b^{ref}(\tau)v_b(\tau) - p_w^{ref}(\tau) - p_s^{ref}(\tau) - p_{wv}^{ref}(\tau)\right)^2 d\tau$$
$$+ \beta(1 - I_s)\int_0^{N\Delta}\frac{p_s^{ref}(\tau)}{p_W^{ref}(\tau)}d\tau + \gamma\int_0^{N\Delta} d_b(\tau)\,d\tau + \in\int_0^{N\Delta}\left(s_t(\tau) - s_t^{opt}\right)^2 d\tau + \rho\int_0^{N\Delta} i_b^{ref}(\tau)^2 d\tau$$
$$+ \theta\frac{\int_0^{N\Delta} p_{RO}(\tau)d\tau}{\int_0^{N\Delta} F_p(\tau)d\tau}$$
$$+ k1\int_0^{N\Delta}\frac{I_s}{p_w^{ref}(\tau) + C_w}d\tau$$
$$+ k2\int_0^{N\Delta}\frac{I_s}{p_s^{ref}(\tau) + C_s}d\tau + k3\int_0^{N\Delta}\frac{I_s}{p_{wv}^{ref}(\tau) + C_{wv}} \qquad 14$$

Where, N = prediction horizon of the MPC, Δ = sampling time, $\alpha, \beta, \gamma, \epsilon, \rho, \theta, k1, k2, k3$ are positive weighting factors, and C_w, C_s, C_{wv} are positive constants.

The first term of the cost function is for standalone operating mode, is difference between the energy generated by the integrated system and the total power for fresh water production (RO) and battery bank, accordingly the energy generation meets total power demand optimally.

The second term is for also standalone mode only, i.e. wind subsystem is active as the primary generation unit and the solar unit is activated when necessary.

The third term implies that the battery should be charged in case of the battery is not completely charged. The fourth term is to optimally maintain the water level in the storage tank around optimal level. The fifth term is to prefer the small charge currents. The sixth term minimized the power consumption for per unit fresh water produced.

When the integrated system is connected with the electric grid then last two terms gets activated and forces the wind, solar and wave to electric generating unit to operate at their maximum capacity. The proposed MPC will work in this way, defined below, at point t_k

$$\min_{p_W^{ref}, p_s^{ref}, p_{wv}^{ref}, i_b^{ref}, v_T^{ref} \in S(\Delta)} J(t_k) \qquad 15.1$$

s.t. $0 \le p_W^{ref}(\tau) \le \min_\tau \{p_W^{max}(\tau)\}, \tau \in [t_{k+j}, t_{k+j+1}]$ 15.2

$0 \le p_s^{ref}(\tau) \le \min_\tau\{p_s^{max}(\tau)\},\ \tau\in[t_{k+j}, t_{k+j+1}]$ 15.3

$0 \le p_{wv}^{ref}(\tau) \le \min_\tau\{p_{wv}^{max}(\tau)\},\ \tau\in[t_{k+j}, t_{k+j+1}]$ 15c

$F_p^{min} \le F_p(\tau) \le F_p^{max}$ 15d

$0 \le d_b(\tau) \le d_b^{max}$ 15e

$s_t^{min} \le s_t(\tau) \le s_t^{max}$ 15f

$i_b^{ref}(\tau) \le i_b^{max}(s_b(\tau))$ 15g

$\dot{\tilde{x}}_s(\tau) = f_s(\tilde{x}_f(\tau), \tilde{x}_s(\tau))$ 15h

$0 = f_f\left(\tilde{x}_f(\tau), \tilde{x}_s(\tau)\right) + gf(\tilde{x}_f(\tau), \tilde{x}_s(\tau))u^{ref}$ 15i

$h(\tilde{x}(\tau)) = 0$ 15j

$\tilde{x}_s(0) = x_s(t_k)$ 15k

Where, $S(\Delta)$ stands for piece-wise constant functions, $j = 0, \dots\dots, N-1$, $\tilde{x}$ is representing the expected state of the system. $x(t_k)$ is the state at time t_k, u^{ref} is the steady state control input obtained based on optimal reference calculated by the MPC.

The constraints of Eq.15.1, 15.2 and 15.3 require that the computed wind, wave and solar subsystems' power references should be smaller than the minimum of the maximum available within each sampling interval. Note that the future maximum available power for the wind, wave and the solar sub-systems are estimated using the information of future weather conditions forecast [9], [11]. The constraint of Eq. 15d puts upper and lower limits (F_p^{max} and F_p^{min}, respectively) on the fresh water (permeate) flow rate (F_p)for equipment safety of the membrane module in the RO subsystem. The constraint of Eq. 15e takes care that the DOD of battery bank doesn't not exceed d_b^{max}. The constraint of Eq. 15f imposes upper and lower limits on storage tank water level. The constraint of Eq. 15g puts an upper limit on the charge current of the battery bank. Note that in the MPC design, only slow system dynamics are considered [i.e., the constraints of Eq. 15h– 15k];, the fast system kinematics used in the MPC are estimated by the operating trajectories computed for future (decision variables for MPC) [the constraint of Eq. 15i]. For example, in the calculation of future $(F_p(\tau))$ the fast state v_r is considered to be equal to v_r^{ref}. The optimal solution to the optimization problem of Eq.15 as given below:

$p_w^{ref,*}(\tau|t_k), p_s^{ref,*}(\tau|t_k), p_{wv}^{ref,*}(\tau|t_k), i_b^{ref,*}(\tau|t_k), u_r^{ref,*}(\tau|t_k)$

The power generation from the wind, solar, wave plants at the reference point, and battery charge and discharge current and RO retentate flow values referred to local controller by the SCS of eq-(15) are specified as follows,

$$p_w^{ref,*}(t) = p_w^{ref,*}(t|t_k), \quad \forall t \in [t_k, t_{k+1}]$$
$$p_s^{ref,*}(t) = p_s^{ref,*}(t|t_k), \quad \forall t \in [t_k, t_{k+1}]$$
$$p_{wv}^{ref,*}(t) = p_{wv}^{ref,*}(t|t_k), \quad \forall t \in [t_k, t_{k+1}]$$
$$i_b^{ref,*}(t) = i_b^{ref,*}(t|t_k), \quad \forall t \in [t_k, t_{k+1}]$$
$$u_r^{ref,*}(t) = u_r^{ref,*}(t|t_k), \quad \forall t \in [t_k, t_{k+1}] \quad (16)$$

The constraints of Eq.15b – 15k are inspired by results on the design of Lyapunov based model predictive control systems (please see [14], [15]). In this work, we consider that the integrated system already operates in normal operating conditions, and do not address the issues related to system startup or shut down.

Local controllers ensure the stability of the system and the supervisory MPC coordinates the local controllers act to improve the overall operation performance.

To carry out optimization of the integrated system for real-time long-term (e.g., for hours), it is essential to reduce the model used in the MPC formulation by taking into account the two-time-scale dynamics of integrated system.

RESULTS AND DISCUSSION

In this section the results of the simulation are discussed. Several sets of experimental simulations has been done to demonstrate the functionability and working of designed supervisory MPC related to the wind-solar-wave combined system. The sampling time is chosen as $\Delta = 1$ hr. considering the water demand which is generally follows periodic data table, and the prediction window has been taken N=24 hr. The weighting factors of the relevant cost function are taken as: $\alpha = 1.8 * 10^{-7}, \beta = 0.001, \gamma = 0.001, \epsilon = 0.01, \rho = 0.05 * 10^{-9}, \theta = 2 * 10^{-7}, k1 = 0.1, k2 = 0.1, k3 = 0.1$.

The values of the weighting factors of this cost function are determined by a trial-and-error approach. The average simulation run time of this supervisory MPC is near about 9 sec. The efficiency of the RO water pump is considered as η=0.7, and the maximum limit of d_b is $d_b^{max} = 0.8$, and the lower limit of F_p is $F_p^{mim} = 0.1814\ m^3/hr$ and upper limit is $F_p^{max} = 3.9918\ m^3/hr$, and the min and max value of s_t are $s_t^{mim} = 0$ and $s_t^{max} = 1$, respectively.

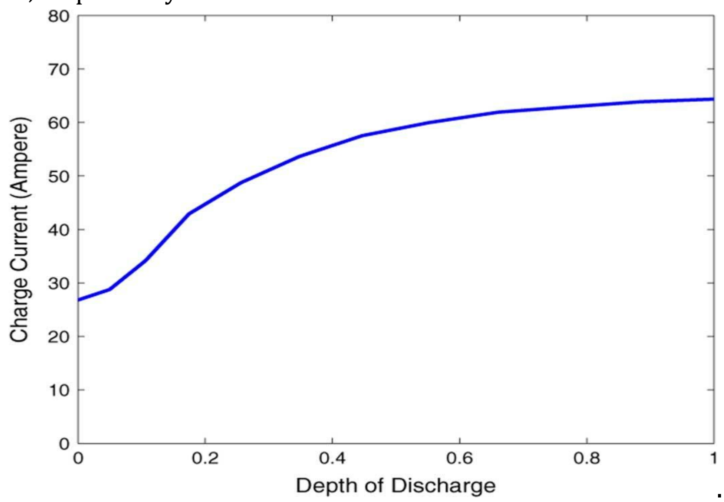

Fig. 3. Upper limit of battery charge current.

The upper limit of the battery charge current is a function of d_b as shown in Fig. 3. In general in all localities there is a water demand data for daily basis, here the water demand for future 24 hours has been estimated based on water demand data available in general (a sample data for a society) . The RO subsystem will produce necessary amount of water according to that data. For wind –solar-wave subsystems a sample forecast data has been taken as input and 8 am to next day 8 am window taken for wind, solar, wave condition forecast and is shown below. One hour deviation and disturbances is taken to the forecast data to make it more realistic and practical.

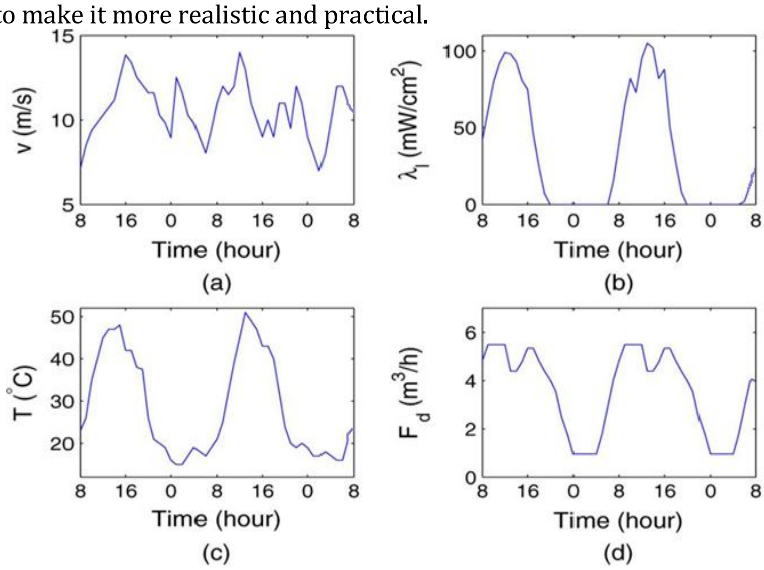

Fig. 4. Weather forecast and water demand: (a) Wind speed (v), (b) Insolation (λ_l),(c) solar PV panel temperature (T), (d) Water demand (F_d)

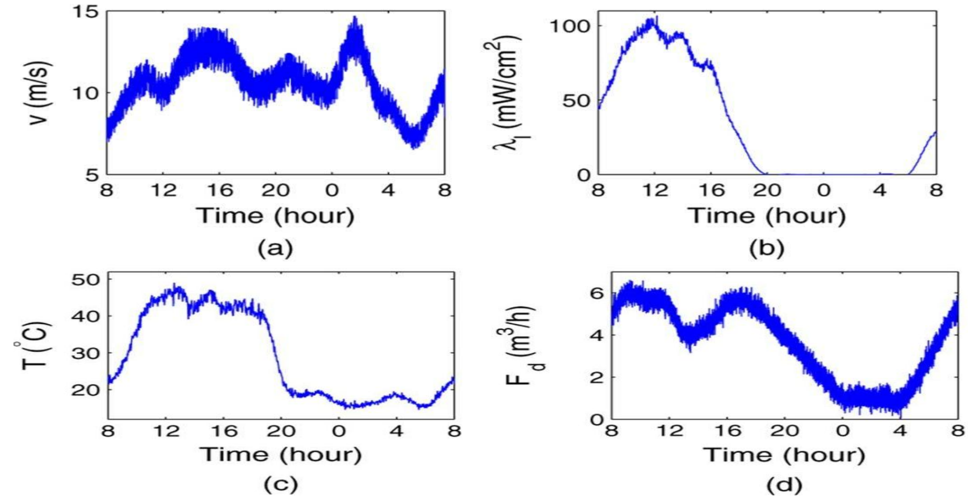

Fig. 5. Weather and water demand: (a) Wind speed (v). (b) insolation (λ_l) (c) PV panel temperature (T) (d) water demand (F_d)

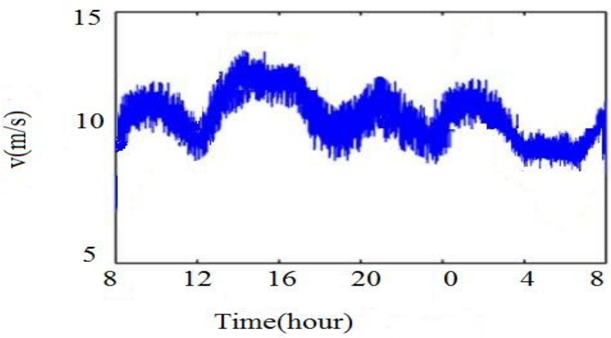

Fig.6 wave condition (wave velocity with respect to time)

Standalone Operating Mode:

In this standalone mode operating mode ($I_g = 0$), power generated by wind, solar, wave sub systems is totally consumed by the water RO plant and/or can be stored in the battery bank and not connected to the electricity distribution grid. The wind, wave and solar subsystem power supply and retentate flow rate are optimized by the supervisory MPC, while the reference for the battery current is inactive in the MPC optimization problem. Eq. 13 shows the current through the battery bank, is determined with the help of current balance around the inverter. For each hour of operation, the wind/solar local controllers operate to drive the wind mill and the solar PV system to generate power according to the reference values, respectively. Fig. 5(a) shows the power generation for wind subsystem. When the enough wind speed, sun light is not available then the local controller switches to MPPT mode. Fig. 5(c) shows the power generation for solar subsystem. When wind or solar power is not sufficient to meet the required RO power (during 8 A.M to 1 P.M and during 4 A.M to 8 A.M) then the power short fall meets by the battery current. Other times, extra power generation is used to charge the battery. The supervisory MPC is capable of producing smooth water production by considering the future state variation in coordination with the subsystems. Fig. 7(a) shows smooth water production through the day, a despite dramatically varying water demand and weather conditions. Fig. 7(b) shows the recharging state of battery and water tank storage condition.

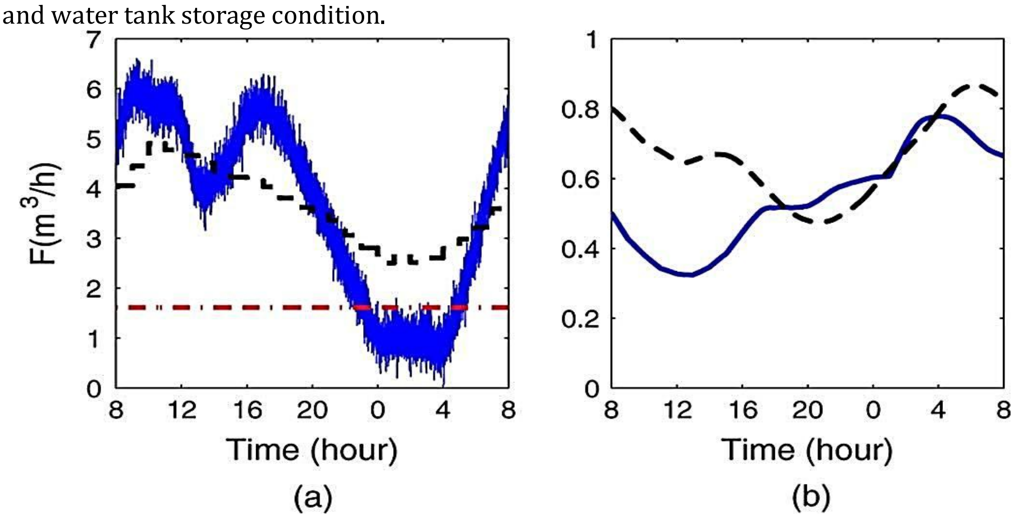

Fig7. (a) Rate of water demand F_d(solid line) and permeate flow rate F_p (dashed line). (b) Battery state of charge s_b (solid line) and tank state of storage s_t (dashed line).

Grid Connected Operating Mode:

The next step is to do the simulation for grid connected operating mode where the integrated wind, wave, solar, RO system operates in electric grid connected mode ($I_g = 1$), Where the wind, solar, wave subsystem are forced to track the heights power generation points all the times and optimize the trajectory and retentate flow rate at every sampling interval. The study compared the proposed supervisory MPC with a reference control strategy without accounting optimality. The reference control strategy is as follows:

1) Wind/solar subsystems follows all the time maximum power generation points;

2) Tank state of storage exceeds 80% (0.8), the RO produces fresh water (t $F_p=F_p^{min}$); for below 60 % (0.6), the RO produces fresh water ($F_p=F_p^{max}$); else the RO produces water based on the next hour water demand;

3) Extra produced energy is first used to charge the battery bank and when battery bank is fully charged or the charge current hits the upper bound the extra produced energy is sent to the electricity distribution grid;

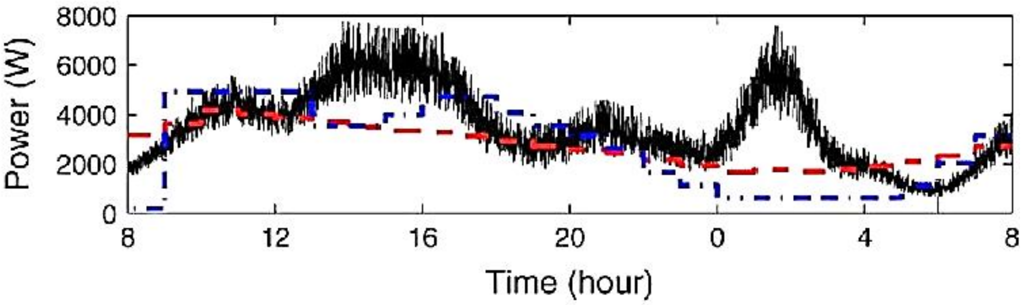

Fig. 8.Generated power $p_w + p_{wv} + p_s$ (solid line) and total power demand p_{RO} under the supervisory MPC (dashed line) and under the reference control strategy (dashed-dotted line).

The permeate(i.e. fresh water output) flow rate consumes less power for per unit of water produced (during 1 P.M to 2 P.M and from 10 P.M to 7 A.M) for simple reference control in compared with supervisory MPC due to the former is closer to the optimal level. For the entire day, average power consumption for water production (per m³) is 2.94×10^6 J/m³ (reference control) and is 2.74×10^6 J/m³ (supervisory MPC), which is 7.06% less than the reference control strategy. Fig. 10 shows comparison results between battery charge/discharge currents for supervisory MPC and reference control. Figs. 8 and 9(a) shows the RO system provides smoother fresh water production when operated under the supervisory MPC. Fig. 9(b) shows reduced average energy consumption in compared with reference control. The result of optimization for battery maintenance shows that the charge/discharge process is more smooth for the supervisory MPC.

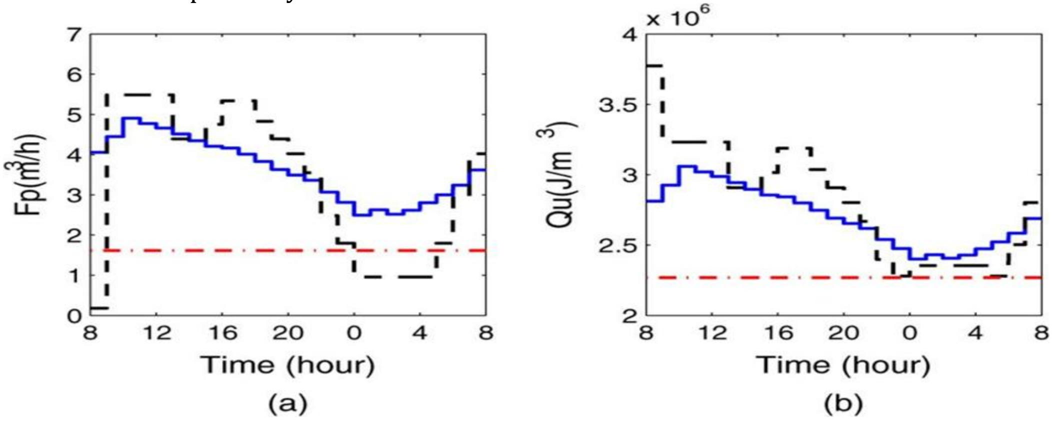

Fig.9. (a) Permeate flow rate under the supervisory MPC, (b) Power consumption (for per m³) of water production (solid line for supervisory MPC, dashed line for reference control and dashed-dotted line for minimum power consumption for per unit fresh water production)

Fig. 11(a) and (b) shows the changes of the permeate(fresh water) flow rate and the corresponding power consumption per unit of water production for the two cases such as (1) only consider water demand for next hour and daily average fresh water demand in the place of the future 24-hr, 2) only consider weather condition forecast for next 1 hour and the corresponding wind speed (daily average), insolation and PV cell average temperature (daytime and night)).The results shows that permeate flow rate trajectory for less water demand forecast deviates from the trajectory obtained with 24-hr weather condition and water demand.

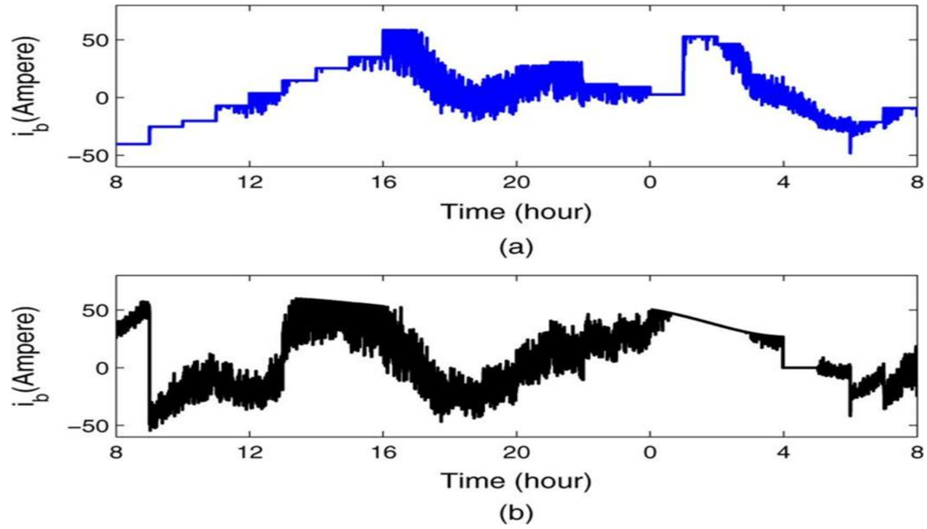

Fig. 10. Battery charge/discharge current (a) supervisory MPC (b) Reference strategy.

Average power consumption of water production (per m^3) in first and second cases surpasses the case with 24-hr forecast information available by 2.92% and less than 0.1%, respectively.

From the simulation results, the supervisory MPC has stronger dependence on the forecast of future water demand in comparison with the forecast of future weather information. In the simulations, we compared the performance of this proposed supervisory MPC with that of an intuitive and standard reference control strategy. We note that the use of linear control (or of other control strategies) at the supervisory layer would potentially lead to improved results over the standard reference strategy but still it would not make possible the incorporation of constraints and complex cost functions in control problem formulation and solution, as it is done with the proposed supervisory MPC. We also note that linear MPC could also be used as the supervisory control system but the system model is nonlinear and repeated linearization would be required to implement linear MPC.

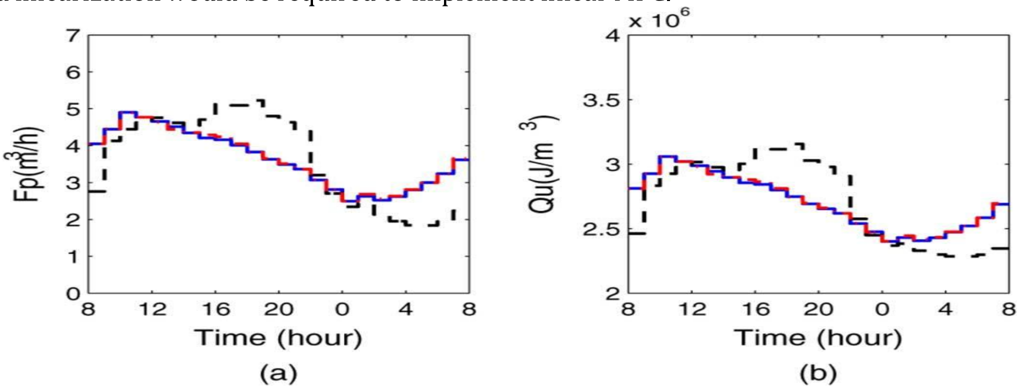

Fig. 11. (a) Permeate flow rate under supervisory MPC , (b) Power consumption (per m^3) for fresh water production (solid line read for 24-hr forecast weather conditions and water demand, dashed line for only 1-hr water demand forecast and 24-hr weather forecast and dashed-dotted line for only 1-hr weather prediction and 24-hr water demand).

CONCLUSIONS

In this work, a supervisory MPC was designed to operate with integrated wind, solar, wave, RO system and energy savings Optimally. The supervisory MPC coordinates with the wind, solar, wave and wave subsystems and the battery to meet the energy demand of RO subsystem to get desired amount of fresh water production. The computational efficiency of supervisory MPC is improved by using two-time-scale dynamics of integrated system. Simulations results of supervisory MPC illustrated its applicability and effectiveness.

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