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Optimal Power Flow Using LQR-Based CCVS Inverter for the Grid-Integrated Renewable Energy System

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Abstract - *This paper proposes an effective control method for the actual and reactive power flow between the renewable energy system (RES) and the grid using a linear quadratic regulator (LQR) to a current-controlled voltage source inverter (CCVSI). Additionally, it makes up for the harmonic current components that the load draws from the grid terminal. The reduced-order state-space model of the three-phase grid-connected renewable energy system is developed using a simplified equivalent circuit. Using fewer weighing variables in LQR makes control law analysis and design simpler. To manage the real and reactive power to the grid and reduce total harmonic distortion (THD), the extension is real-reactive power (p-q) approach implemented in an a-b-c frame is used to generate the reference current.*

Key Words: Optimal Power Flow, RES, LQR, CCVSI.

I INTRODUCTION

Due to the enormous increase in power demand, electrical power systems are getting overloaded [1,2]. This leads to an exponential increase in the usage of renewable energy sources (RES). With the advent of power electronic converters, RES is effectively integrated with the electrical power system [3,4]. However, the usage of power electronic devices and non-linear loads deteriorate the quality of power in the electrical system [5,6].

Therefore, an appropriate regulatory framework is to be followed for the distribution system to guarantee the reliable and efficient operation of the system. In addition to the power converter, shunt active power filters [8-12] are used to mitigate power quality issues. This increases the additional hardware cost. Hence, a current-controlled voltage source inverter (CCVSI) is employed in this work for the twofold purpose of power conversion and power quality improvement.[13] The performance of CCVSI is based on the reference current generation.[14]

The generated reference currents compensate for the reactive and harmonic components. Various techniques are presented in the literature [15-18] to generate reference currents. In this work, instantaneous p-q theory is used. It uses instantaneous quantities instead of average quantities. It eliminates the reactive power in transient states and harmonic currents. [19]

A control technique is essential to track the reference currents. In literature, many researchers proposed several control techniques to integrate the RES with the grid. The implementation of a hysteresis controller is simple, but its variable switching frequency causes resonance and switching losses. Fixed switching frequency is obtained by comparing the output with the carrier wave in a conventional Proportional Integral (PI) controller with pulse width modulation (PWM). [19,20]

But the steady-state error is present in the output if a sinusoidal reference is followed. The steady-state error is eliminated using a proportional Resonant (PR) controller, but its performance depends on the controller which operates in resonant frequency. In terms of response profile, control effort requirement, and robustness concerning system nonlinearities, the optimal Linear Quadratic Regulator (LQR) is superior. Using LQR, the optimal pole placement controller is used in this work to track the sinusoidal references with the fixed switching frequency, good stability margins, and transient response. To prove the supremacy of LQR, the hysteresis controller is compared.[21]

Several current control techniques are proposed in the literature to integrate renewable sources in the grid [22–31]. The hysteresis controller is simple to implement but results in variable switching frequency causing resonance and more switching losses.

The switching frequency can be fixed by a carrier wave in a conventional proportional-integral (PI) controller with pulse width modulation (PWM) control. But there exists a steady-state error whenever sinusoidal references are used. This may not be preferable for certain applications. [32]

A controller that eliminates the steady-state error while regulating the sinusoidal signals is a proportional resonant (PR) controller, but its performance depends on the resonant frequency at which the controller operates. This frequency has to be adjusted in the method that matches the grid frequency. Yet, another type of controller namely the deadbeat controller is widely employed due to its good tracking in regulating the sinusoidal signals. If PWM and saturation of the control actions are considered, it exhibits a slow response. In comparison with conventional controllers, the controller provides better performance by offering low grid current THD even in the presence of non-linear loads, but it has slow dynamics [32].

The literature review reveals that the optimal LQR is superior in terms of response profile, and control effort required, and is robust with respect to system non-linearities. LQR provides a systematic way of computing the state feedback gain matrix (K) that makes it more advantageous than the pole placement technique [33]. Hence, in this work, LQR, the optimal pole placement controller is used to track the sinusoidal reference current with the fixed switching frequency, good transient response, and excellent stability margins. Many researchers [33-35] designed the control law using LQR for shunt active power filters to compensate only the reactive power with more weighing variables under balanced conditions.

The present work is designed from the single-phase equivalent circuit that minimizes the number of weighing variables and hence reduces the complexity.

Microgrids are beneficial for many reasons. In addition to improving energy efficiency, like most advanced building control strategies or energy efficiency measures[36-39] Microgrids need control and management at different levels to allow the inclusion of renewable energy sources.[40]The development of microgrids is an advantageous option for integrating rapidly growing renewable energies.[41]

The microgrid control schemes are classified as centralized, decentralized, and distributed.[42] Microgrids usually represent a single organized power subsystem having a number of distributed generation (DG) sources[43] Different optimization methods applied to different energy domain areas are reviewed.[44] MPC algorithms depend heavily on precise measurements of process variables that are provided by sensors. In some versions of automatic control systems.[45] The microgrid operation control strategy takes the energy storage system (ESS) as the main controlled unit to suppress power fluctuations and distributes the power of distributed power sources according to the SOC.[46] The model can be derived analytically, but more typically it is provided by simple experiments, or in the adaptive context by recursive estimation.[47]

II SYSTEM DESCRIPTION

Different RESs are connected to the grid through the power electronic converters, which is shown in Fig.1

The maximum power is derived from RES using a power electronic interface which is controlled by controller -1. The extracted energy from RES is stored in the storage device, and it is delivered to the grid through CCVSI which is controlled by the controller- 2. Controller-2 synchronizes and monitors the grid, reduces the harmonics at the point of common coupling (PCC), and controls the real and reactive power flow between RES, grid, and load. [48-50]

Depending on the availability of RES power (PRES), the modes of operation are divided into two. In the first mode of operation, PRES is considered as lower than the load power (PL). Hence the load is shared by the RES and grid. PRES is taken as greater than load power in the second mode of operation. Here the excess power generated by the RES is supplied to the grid.

The dc link is modeled as a dc source as shown in Fig. 2 with the assumption of maximum power extracted from RES is stored in the battery. The amount of stored energy depends on the power availability in RES.

Through CCVSI, filter inductors (Lfa, Lfb, Lfc), and their leakage resistances (Rfa, Rfb, Rfc), the dc source is connected to the grid. The grid inductances and its leakage resistances are represented as Lga, Lgb, Lgc, and Rga, Rgb, Rgc respectively. [50]

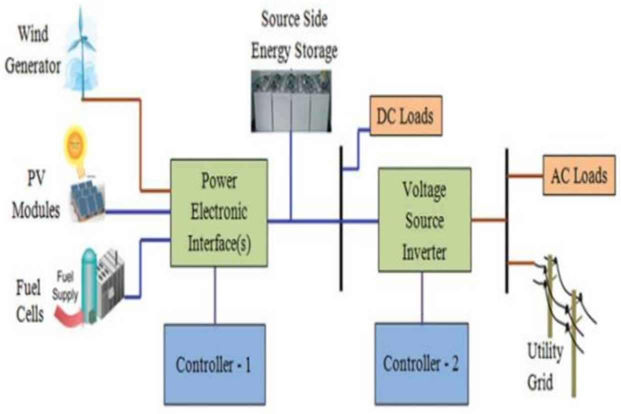


Fig. 1 General schematic of RES integrated with grid [1]

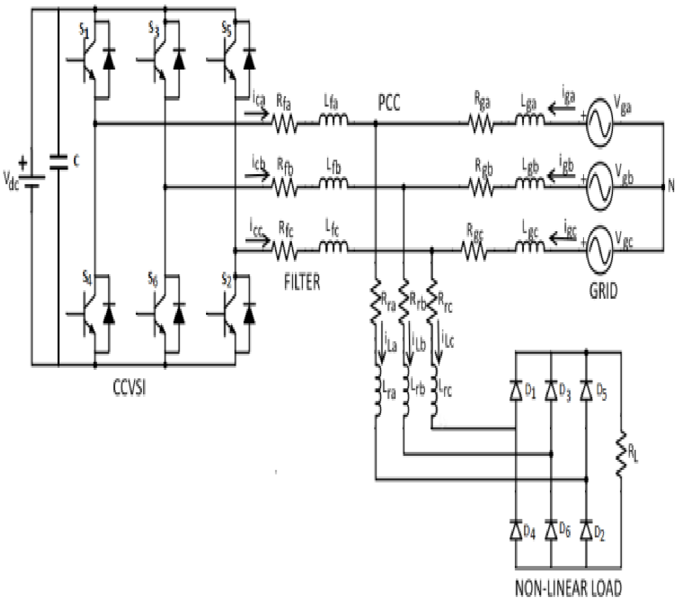


Fig. 2 Power Circuit Diagram of the grid-connected inverter [1]

The diode bridge rectifier feeding a resistance which is a non-linear load is connected to the PCC through rectifier link inductors (Lra, Lrb, Lrc) and its corresponding leakage resistances (Rra, Rrb, Rrc). The non-linear load draws harmonic and reactive power components from PCC which affects the quality of power in the grid. [2] Although input and output constraints are basically treated and optimal control has been obtained.[1]

To improve the quality of power in the grid, the switches in the CCVSI are properly switched by a suitable controller in such a way that the inverter currents (ica, icb, icc) follow their corresponding reference currents (ica *, icb *, icc *). Thus, the reference currents are generated to maintain the grid currents (iga, igb, igc) sinusoidal with unity power factor. In this work, the reference currents are generated using instantaneous p-q theory and the controllers used are hysteresis and LQR.[1]

III REFERENCE CURRENT GENERATION

The p-q theory is based on instantaneous values instead of average values. It uses the αβ0 transformation known as the Clarke transformation to obtain the reference currents. While generating reference currents the amount of real power flow from RES to the grid/load, reactive power compensation, and harmonic reduction is taken into consideration [1]

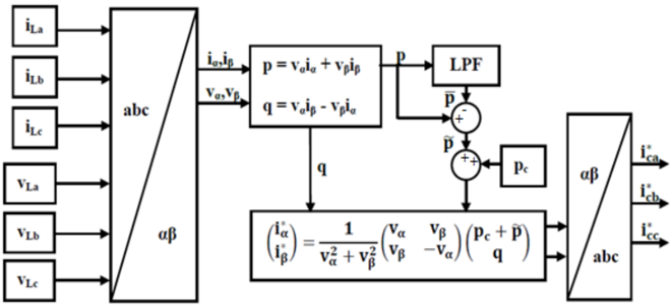


Fig. 3 Reference current generation using instantaneous p-q [1]

IV DESIGN OF CONTROLLERS

To track the reference currents, the pulses are generated using a hysteresis controller and LQR technique. [1]

A. Hysteresis Controller (HC)

This is a simple and conventional technique to implement. It does not depend on load parameters. The main disadvantage is its variable switching frequency which leads to resonance problems and high switching losses. The implementation of the hysteresis controller per phase is depicted in Fig. 4. The error is calculated by finding the difference between the reference inverter current and the actual inverter current. According to the error, the pulses are generated. The control logic is [1]

$$u = \begin{cases} -1, & i \geq i_c^* + h \\ 1, & i \leq i_c^* - h \end{cases} \qquad \text{---(1)}$$

The actual current is forced to follow the reference current by making the actual current stay within the hysteresis band.[3]

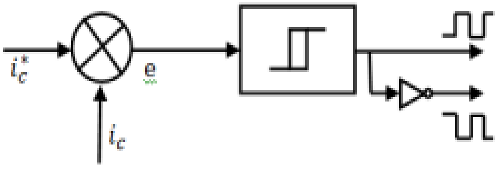


Fig. 4 Implementation of Hysteresis Controller per phase [1]

B. Linear Quadratic Regulator (LQR)

To minimize the tracking error, an optimal control problem, LQR is used to determine the control strategies over a period of time. The drawback of variable switching frequency present in the hysteresis controller is eradicated using LQR by comparing the error with the constant frequency triangular wave. Initially, mathematical modeling is derived to determine the control law of LQR. To simplify the modeling, a simplified equivalent circuit shown in Fig. 5 is developed for the three-phase grid-connected renewable energy system [21]. In the figure, u.Vdc represents the CCVSI output voltage which is the control variable for switching, Rf, and Lf are the resistance and inductance of filter per phase, Rg and Lg are the resistance and inductance of grid per phase, RL and LL are the resistance and inductance of load per phase and vg is the grid voltage.

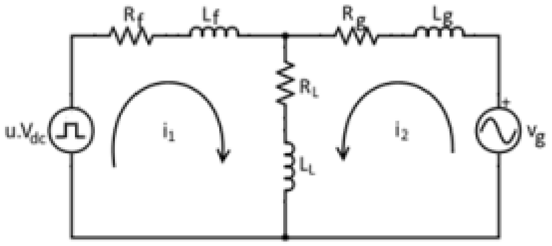


Fig. 5 Single Phase Equivalent Circuit of Grid Connected CCVSI [1]

Applying Kirchoff's voltage law, the differential equations of the circuit given in Fig. 5 are written as[1]

$R_f i_1 + L_f(di_1/dt)+R_L(i_1-i_2)+L_L(d/dt[i_1+i_2]) = uV_{dc}$ ....(2)

$R_g i_2 + L_g(di_2/dt)+R_L(i_1-i_2)+L_L(d/dt[i_1+i_2]) = Vg$ ....(3)

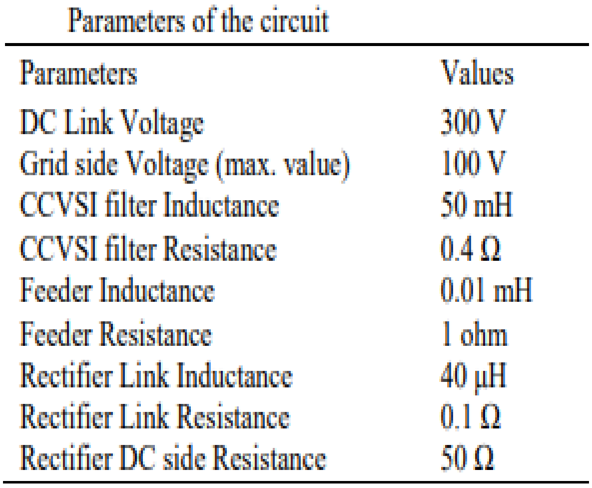
Taking loop currents i1 and i2 as state variables x1 and x2 respectively.

$$\begin{pmatrix}\dot{x}_1\\ \dot{x}_2\end{pmatrix}=\begin{pmatrix}a_{11} & a_{12}\\ a_{21} & a_{22}\end{pmatrix}\begin{pmatrix}x_1\\ x_2\end{pmatrix}+\begin{pmatrix}b_{11} & b_{12}\\ b_{21} & b_{22}\end{pmatrix}\begin{pmatrix}v_g\\ u\end{pmatrix}$$ ....(4)

the state equations are written below

$X' = AX + BU$ ....(5)

Table 1: CCVSI Parameters [50]



Parameters of the circuit

Parameters	Values
DC Link Voltage	300 V
Grid side Voltage (max. value)	100 V
CCVSI filter Inductance	50 mH
CCVSI filter Resistance	0.4 Ω
Feeder Inductance	0.01 mH
Feeder Resistance	1 ohm
Rectifier Link Inductance	40 μH
Rectifier Link Resistance	0.1 Ω
Rectifier DC side Resistance	50 Ω

$$a_{11}=\frac{-(R_f+R_L)L_g-R_fL_L}{(L_f+L_L)L_g+L_fL_L}\quad a_{12}=\frac{-R_LL_g+R_gL_L}{(L_f+L_L)L_g+L_fL_L}$$

$$a_{21}=\frac{-R_LL_f+R_fL_L}{(L_f+L_L)L_g+L_fL_L}\quad a_{22}=\frac{-(L_f+L_L)R_g-R_LL_f}{(L_f+L_L)L_g+L_fL_L}$$

$$b_{11}=\frac{-L_L}{(L_f+L_L)L_g+L_fL_L}\quad b_{12}=\frac{V_{dc}L_g+V_{dc}L_L}{(L_f+L_L)L_g+L_fL_L}$$

$$b_{21}=\frac{L_f+L_L}{(L_f+L_L)L_g+L_fL_L}\quad b_{22}=\frac{-V_{dc}L_L}{(L_f+L_L)L_g+L_fL_L}$$

............(6)

a_{11}= -2.64 a_{12}=15.6
a_{21}=-1993.3 a_{22}=-22012.5

b_{11}= -16 b_{12}=5999
b_{21}=20213.1 b_{22}=-4799.2 ....(7)

In the LQR technique, the error is minimized by deriving the optimal state feedback control law to place the poles in desired locations as [1]

$u = -K(X^* - X)$ ....(8)

Where X is the actual state vector, X^* is the desired state vector and K is the feedback gain matrix. The value of K is found by solving the Algebraic Riccati Equation (ARE) of [1]

$A^TP+PA+Q-PBR^{-1}B^TP=0$..........(9)
and the solution is

$K = R^{-1}B^TP$ ....(10)

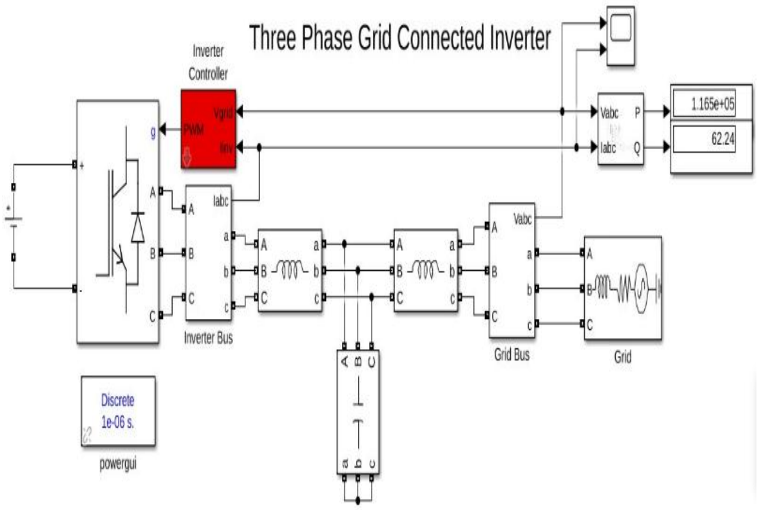


Fig. 6 Simulink Model of Three-Phase Grid-Connected CCVSI [52]

To find the optimized feedback gain K using LQR we follow the procedure given below:

STEP 1: HAMILTONIAN

We define the Hamiltonian H* (also called the Pontryagin H function) at the optimal condition.[51]

$H(\lambda,x,u,t)=\lambda^T(Ax+Bu)+x^T Qx+u^T Ru$ ....(10)

where the costate trajectory is given by λ(t), state and control trajectories x and u

STEP 2: OPTIMAL CONTROL

The optimal control u*(t) is determined by applying the first theorem of the Calculus of Variation [51]

$$\frac{\partial H}{\partial u}=0 \quad \dots\dots(11)$$

This leads to the optimal control u*(t) as [51]

$u^*(t) = -R^{-1}(t)\, B'(t)\, \lambda^*(t)$ ……… (12)

STEP 3: STATE AND COSTATE SYSTEM

$u^*(t) = -R^{-1}(t)\, B'(t)\, \lambda^*(t) \rightarrow (13)$

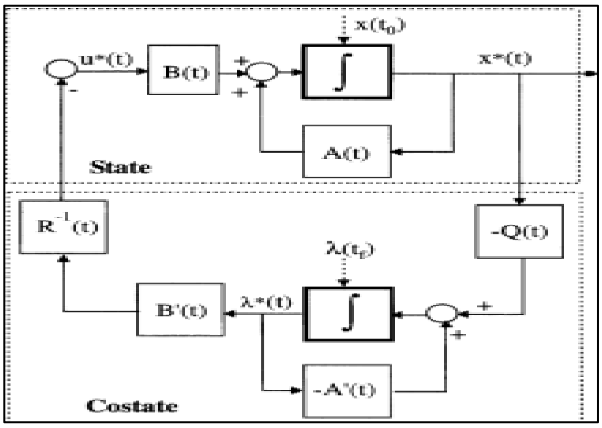


Fig. 7 Implementation of the LQR Controller [50]

STEP 4 CLOSED-LOOP OPTIMAL CONTROL

The values of A and B are from equation (5). Choice of the weighting matrices Q and R. The quality of the control design using LQ method depends on the choice of Q and R

A Standard choice for the matrices Q and R in the LQR cost function is given by Bryson's rule as follows: select Q and R diagonal with

$Q=\begin{pmatrix} a & K \\ K & K^2 \end{pmatrix}$ $R = diagonal(r1, r2, r3)$

$Q=\begin{pmatrix} 2 & 0 \\ 0 & 0 \end{pmatrix}$ $R = (0.5)$

$A^TP + PA + Q - PBR^{-1}B^TP = 0$

The valuation for P and K are determined using MATLAB

V SIMULATION RESULTS AND DISCUSSION

The optimal power flow system is simulated in MATLAB/SIMULINK environment to compare the potency of the controllers for the specifications shown in Table 1. A three-phase current-controlled voltage source inverter (CCVSI) is controlled for achieving unity power factor at the grid side and low THD in the grid current. The sign convention of real and reactive power of the grid and inverter is taken as positive if the grid/inverter delivers the power towards PCC, and the real and reactive power of the load is taken as positive if the load absorbs power from PCC.[50]

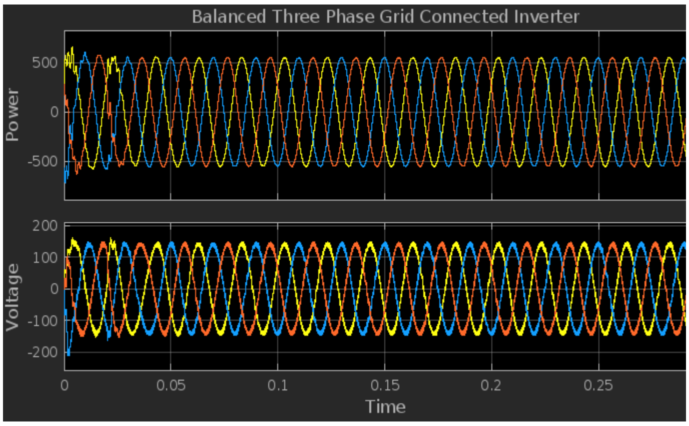


Fig.8 Simulation of Three-Phase grid Connected CCVSI [52]

Mode 1 (t < 0.15 sec, PRES < PL)

In this case, the power generation from RES is lesser than the load power taken. The real power of the load is supplied by the grid and RES, i.e., PL = PRES + Pg. Under this condition, RES and grid supply the real power, and the load absorbs the real power, making PRES, Pg, and PL as positive. Also, the grid voltage and current are in phase with each other. The reactive power (QL) of the load is fully supplied by the VSI (Qc) so as to make the reactive power (Qg) of the grid as zero, i.e., QL = Qc, Qg = 0. Thus, the reactive power of the grid is zero and the real power Pg is positive, the system maintains the unity power factor.[50]

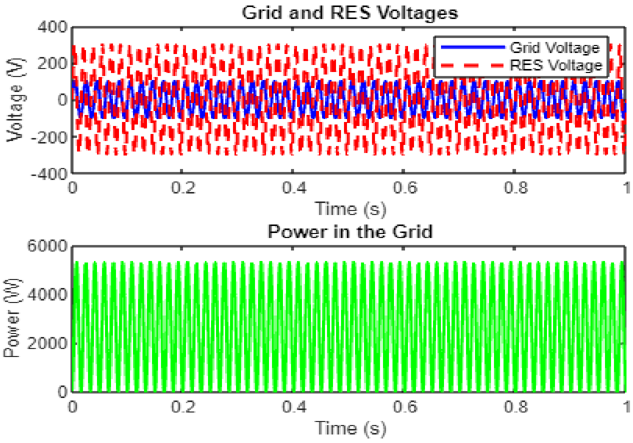


Fig. 9 Simulation of CCVSI grid Power mode 1[52]

Mode 2 (t > 0.15 sec, PRES > PL)

Here, the power generation from RES is greater than load power is considered. The excess RES power is fed to the grid. Hence, the real power is absorbed by the grid and load, and it is delivered by the RES, making PL and PRES as positive and Pg as negative. [1]

The grid voltage and current are out of phase with each other, since the real power is absorbed by the grid. As in mode 1, the load reactive power (QL) is compensated by the VSI making zero reactive power (Qg) in the grid, i.e., QL = Qc, Qg = 0. Thus, the reactive power of the grid is negligible and the real power Pg is negative, the system maintains the unity power factor.[1]

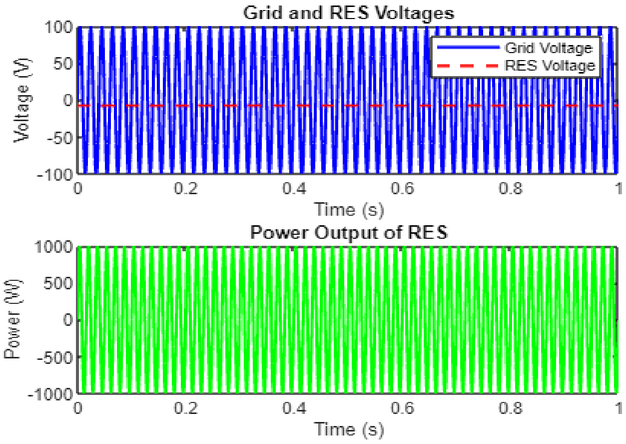


Fig. 10 Simulation of CCVSI grid Power mode 2[52]

Hence, the value of THD under unbalanced conditions is lower than that under balanced conditions in both the methods HC and LQR[50]

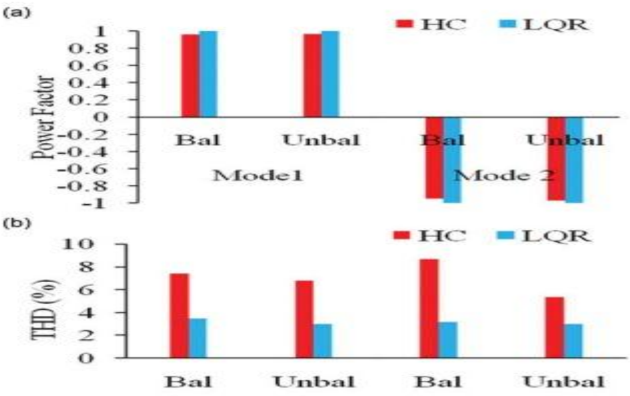


Fig.11 Comparison results for THD and Power Factor [1]

A=
1.0e+04 *

-0.0003 0.0016
-0.1993 -2.2012

B =

1.0e+04 *

-0.0016 0.5999

```
  2.0213                                    -0.4799
P                                                 =

  1.0e-03                                         *

  0.1667                                     0.0001
  0.0001                                     0.0000
L                                                 =

  1.0e+04                                         *

 -1.1989
 -2.2016
K                                                 =

 -0.0022                                    -0.0000
  1.9994   0.0009
```

CONCLUSION

In order to optimize the power flow by regulating the inverter current, this paper introduced linear quadratic regulators. Utilizing instantaneous p-q theory, the CCVSI generates the reference current in order to transmit actual power from RES and balance out reactive power. Instead of average values, this theory makes use of current real and reactive power values. The grid now supplies and receives sinusoidal currents with lower THD and greater power factor thanks to the control schemes. The complexity of the LQR's design is minimized by using a single-phase equivalent circuit of a three-phase grid-integrated renewable energy system. A low THD and a power factor that is closer to unity indicate that LQR has an edge over the hysteresis controller. Utilizing LQR, the optimization was performed using Simulink and Matlab.

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