Reactive Power Control in Grid Connected PV System using Phase Locked Loop Control

Nourhan M. Elbehairy, Rania A. Swief, Amr M. Abdin, T.S. Abdel-Salam

Abstract*:*In this paper, an optimal study is introduced to control the reactive power in an electrical network using a voltage source inverter based photovoltaic system. The control parameter optimization is achieved through a phase locked loop control. The photovoltaic systems are adopted on using multi inverters. Therefore, the analysis of a single inverter control strategy is considered a model for the whole system. The synchronization with the electrical grid is provided using phase locked loop control. According to a certain objective function, the control parameters are optimized and the pulses are generated to the inverter. The simulations are performed using the package of MATLAB/SIMULINK with a double stage PV model. The first stage contains a dc-dc converter to track the maximum power while the other stage includes the voltage source inverter that controlled using the phase locked loop. The simulation results are introduced through different cases of changing irradiance on the PV system.

Keywords* : *Reactive power flow, Voltage source inverter, grid connected PV, Phase locked loop.

I. INTRODUCTION

In the last decades, a great concern is directed to the sources of renewable energy resources. One of the major sources of energy is the solar energy. The photovoltaic systems have been developed greatly to form an increasing percentage of the electricity generation. This percentage reached 2.4% of the whole world-wide electricity generation at the end of the year 2018 [1]. The governments encourage the generation from PV arrays as they have renewable and green energy. This type of generation is also used to increase the level of power quality in electrical networks [2]. This paper focuses on an important issue of power quality which is the reactive power flow.

The grid connected photovoltaic systems incorporates a robust and efficient control strategies and algorithms. These strategies involve some features such as load balancing, compensation of reactive power [3].Agarwal et al. [4] proposed the use of Least Mean Fourth (LMF) algorithm to control the power of grid connected PV systems. In this research, the PV system acts as static compensator to compensate the reactive power. Other references used different topologies to control the operation of interfacing PV systems to the grid. George et al. [5] used the d-q-zero transformation for PV system interfacing control. Singh et al. [6] used the modified instantaneous reactive power theory to provide power factor correction as well as harmonics elimination from the utility side. Keerthana et al. [7] introduced a comparison study for the different interfacing methods in PV systems interfacing used for different objectives. Hussein [8] presented the method of control of a grid connected photovoltaicsystem inverterto Supply powers with different power factors. Savitha et al [9] used the instantaneous PQ theory in the modeling and performance of grid connected PV system.

This paper introduces the using of phase locked loop (PLL) control to manage the reactive power flow in the grid when interfacing a 100 kW photovoltaic station. The system depends on two stage control. The first stage includes a dc-dc converter to provide maximum power point tracking (MPPT) while the second stage consists of the voltage source inverter. The authors presented a novel algorithm for MPPT in [10] under different shading conditions and using modern optimization technique which is the flower pollination algorithm (FPA) and reached very accurate results under different conditions of changing irradiance on each part of the PV array.

The structure of this paper involves an introduction in the first section, while section II introduces a model of the system. Section III presents the mathematical model of the control approach used that depends on the PLL theory. Section IV discusses the simulation and results at different cases and conditions of operation. Finally section V extracts the conclusions outcomes from the research.

II. SYSTEM MODELLING

Fig. 1 introduces the block diagram of the proposed system under study. The system consists of a 100 kW PV station connected to the grid through a double stages interfacing equipment.

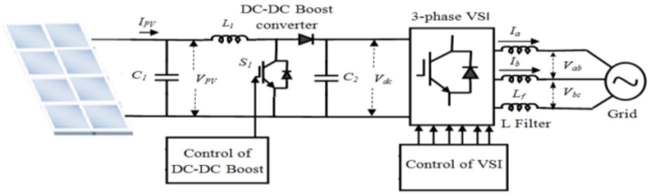

Fig. 1. Block Diagram of PV system connected to grid

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The first stage contains a boost converter in order to detect the maximum power point of the i-v characteristics for the PV array. The output dc link voltage is adjusted to be constant and equals 500 V.
The second stage consists of a three level inverter to transfer the voltage into AC voltage in the range of 260 V rms voltage. Then, a series inductive filter is used to smooth the square pulses voltage shape into a sinusoidal shape with the same level of voltage. The voltage is stepped up through a step up transformer to be connected and interfaced with the grid at a medium voltage level of about 25 kV.
The PV arrays have different models [11]; the selected model of the PV cell is the single diode model which is simple and suitable to be included in the system of PV station interfaced to the electrical grid.
Fig. 2 shows the equivalent circuit of the PV cell with single diode model where Table-I give the characteristics of used module. To choose the number of series and parallel modules to get a maximum capacity of 100 kW connected to 500 V dc link after the boost converter where the PV module used is a 305 watt peak power, the following equations are considered.
Number of series modules considering an output voltage of 260V before the application of boost converter

$$N_s = \frac{V_{dc}}{V_{mp}} = \frac{260}{54.7} = 4.75 \cong 5 \quad (1)$$

The number of parallel strings can be estimated from

$$N_P = \frac{P_{max}/P_{module}}{N_s} = \frac{100x10^3/305}{5} = 65.57 \cong 66 \quad (2)$$

III. PLL CONTROL APPROACH

A phase-locked loop (PLL) is an electronic circuit involves a phase detector, low-pass filter, and voltage-controlled oscillator (VCO). Fig.3. show the structure of PLL. The closed-loop operation of the circuit is to maintain the VCO frequency locked to that of the input signal frequency.

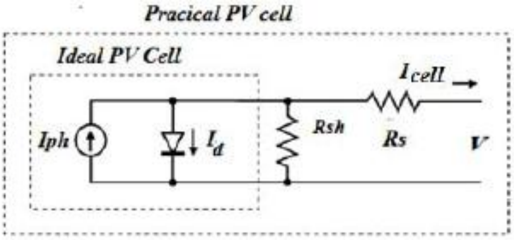

Fig. 2. Single diode model of PV cell

Table- I: characteristics of PV module

Parameter	Value
Model	SunPower SPR-305E-WHT-D
Maximum Power	305 Watt
Number of Cells per module	96
Open Circuit Voltage	64.2 V
Short Circuit current	5.96 A
Voltage at maximum power	54.7 V
Current at maximum power	5.58 A
Reverse saturation current	6.3 x 10^{-12} A
Series parasetic resistance	0.3715 Ω
Shunt parasitic resistance	270 Ω

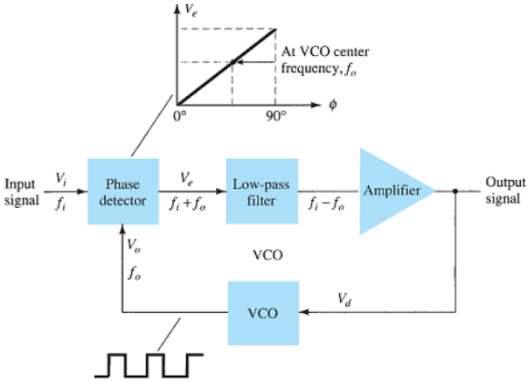

Fig. 3. Block diagram structure of PLL

The aim of PLL in this research is to track the fundamental grid voltage even though that severe harmonics are present. Therefore, the PLL can be regarded in this operation as a band pass filter with zero distortion. Fig. 4 introduces the block diagram of the PLL operation in interfacing the PV system to the electrical grid. The equation involved in the block diagram takes the α-β components of the grid voltage after the transformation from a-b-c sequence and applying some equations to provide the required control.
The value of error into the PI controller that included in the PLL block diagram is given by inspection of Fig.4 and assuming no harmonics exists and the frequency is constant and equals to 60 Hz.

$$Error = U_{grid}.\sin(\theta_{grid}).\cos(\theta_{PLL}) - U_{grid}.\cos(\theta_{grid}).\sin(\theta_{PLL}) \quad (3)$$

Therefore,

$$Error = U_{grid}.\sin(\theta_{grid} - \theta_{PLL}) \quad (4)$$

Using Taylor series and neglecting the high order terms, the previous equation can be approximated to the following equation.

$$Error = U_{grid}.(\theta_{grid} - \theta_{PLL}) \quad (5)$$

The linearized small signal transfer function of the PLL is

$$PLL(s) = \frac{U_{grid}.\mathrm{PI(s)}.\frac{1}{s}}{1 + U_{grid}.\mathrm{PI(s)}.\frac{1}{s}} \quad (6)$$

Then, the final form of the transfer function in the form

$$PLL(s) = \frac{\frac{U_{grid}.K_P}{T_i}(T_i s + 1)}{s^2 + U_{grid}.K_P.s + \frac{U_{grid}.K_P}{T_i}} \quad (7)$$

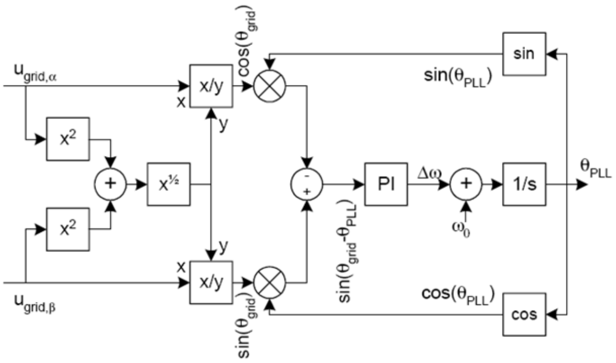

Fig. 4. PLL Algorithm block diagram

IV. SIMULATION AND RESULTS

The model of the grid connected PV system is demonstrated on the MATLAB/SIMULINK package. Fig. 5 presents the model which consists of a 100 kW PV station connected to a dc boost converter to track the maximum power point of the i-v characteristics. After that, the system is connected to an voltage source inverter that is controlled using PLL control. The output ac voltage in stepped up to be connected to the electrical grid at a voltage of 25 kV.

The simulation study cases focus on the reactive power flow coming from the PV system in order to improve the utility power factor. The main parameter that controls the reactive power flow is the reactive current reference inside the controller. Fig. 6 clarifies the control block diagram of the generating pulses controller.

In this block diagram, the PLL measurement block performs a transformation from a-b-c sequence into d-q-0 frame. The dc voltage regulator compares the actual dc link voltage with the reference one to generate the active current reference signal. The reactive current signal is modeled to be input signal combined with the active current reference to be injected to the current regulator. Therefore, with the suitable control gains, the reference voltages are generated in order to maximize the active power and deliver the required reactive power. Finally the inverter pulses are generated.

The different study cases are as follow

1- The PV system acts as an active power supply and does not generate any reactive power
2- The PV system generates the maximum active power with 20 % additional reactive power.
3- The PV system generates the maximum active power with 50 % additional reactive power.
4- The PV system generates the maximum active power as well as the same amount of reactive power.

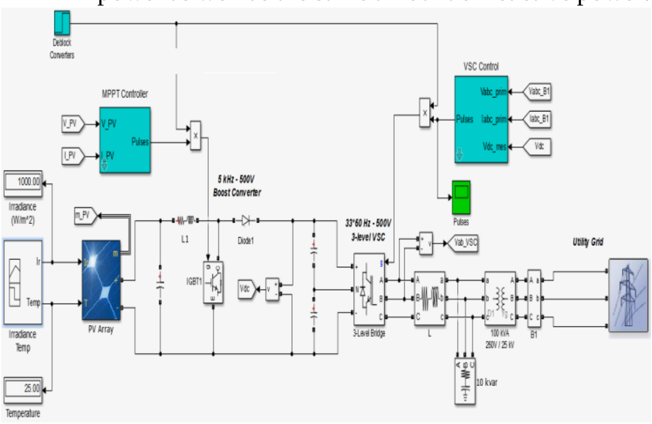

Figure 5 Simulation model of interfacing control

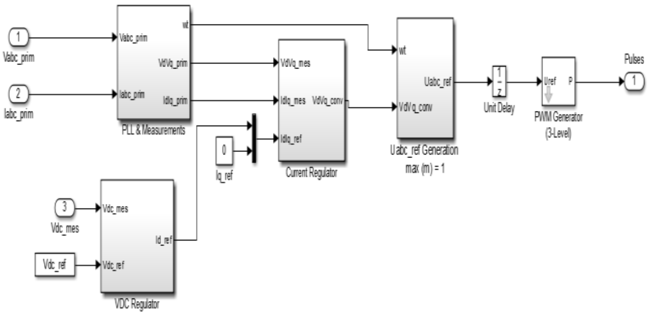

Fig.6. PLL control Algorithm

Fig. 7 show the point of common coupling (PCC) voltage and current while Fig. 8 introduces the variation of active and reactive power in kW and kVAR respectively. Both figures at a zero reference reactive current. It is noticed from the voltage and current waveforms that there is no phase shift between them that means zero phase shift and zero reactive power generated which in assigned in reactive power curve which oscillates around zero value.Fig. 9 show the voltage and current in case of 20% reference reactive current while Fig. 10 Presents the variation of active and reactive power in kW and kVAR respectively at the same case. It is clear from Fig. 9 that there is a small phase shift between the bus voltage and bus current waveforms assigned by horizontal lines on the figure. This phase shift is about 0.52 ms in time and 11.3^o in angle. The results of Fig. 10 clarifies that the reactive power flow from the PV system is settled at 20 kVAR after an interval of transient.

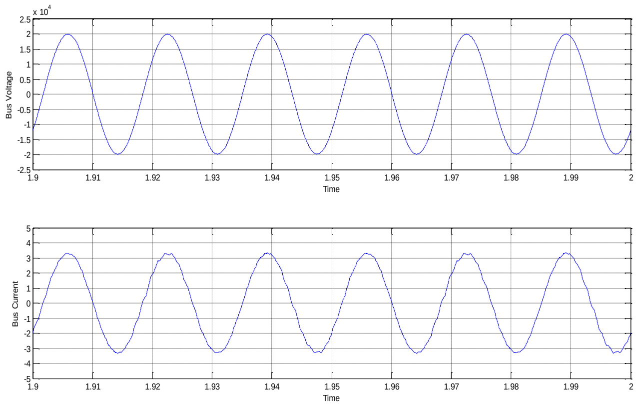

Fig.7. Voltage and current waveforms in case of zero Q

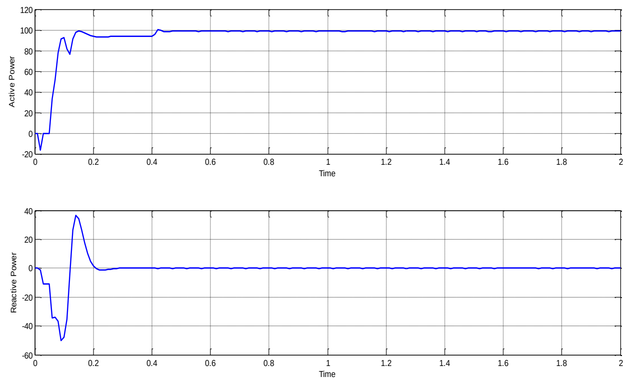

Fig.8. Active and reactive power in case of zero Q

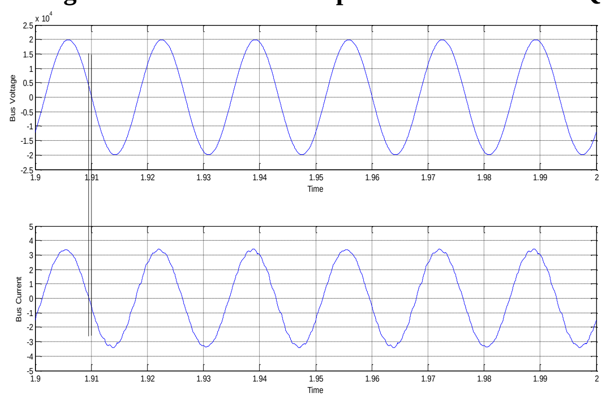

Fig.9. Voltage and current waveforms in case of 20% Q

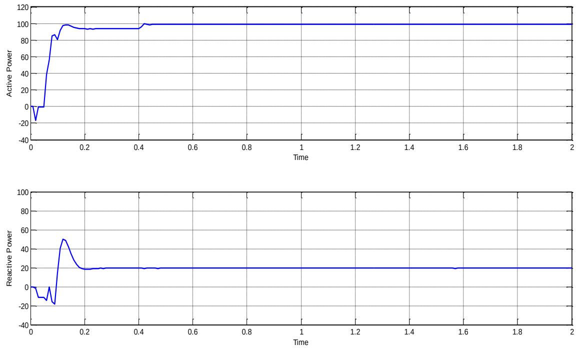

Fig.10. Active and reactive power in case of 20% Q

Additional cases are introduced with higher reactive power compensation levels. A percentage of 50% compensation is introduced in Fig. 11 and Fig. 12. Even 100% compensation can be reached and illustrated in Fig. 13 and Fig. 14.

In Fig. 11, it is clear that the phase shift angle between bus voltage and bus current is increased than the previous cases,this angle reaches 26.6^{o}.In addition, Fig. 12 refers to the increase of injected reactive power to reach 50 kVAR.

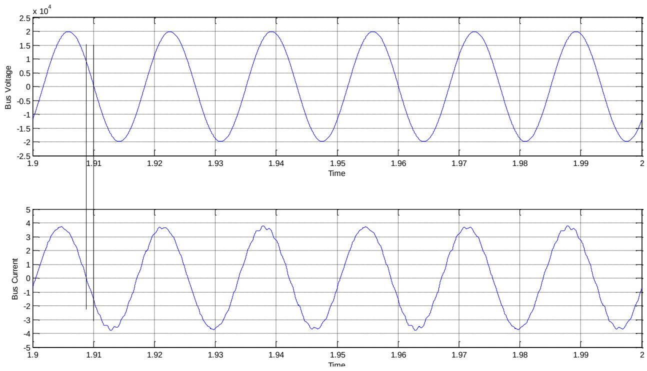

Fig.11. Voltage and current waveforms in case of 50% Q

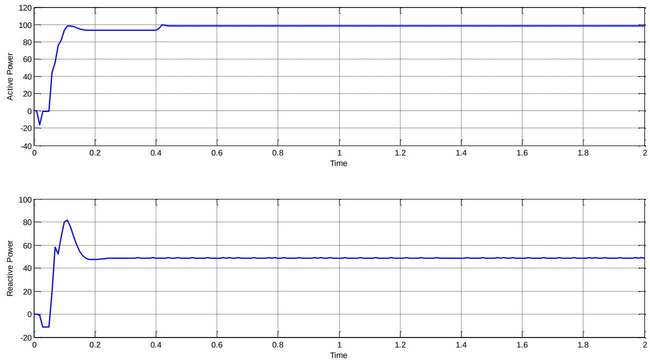

Fig. 12. Active and reactive power in case of 50% Q

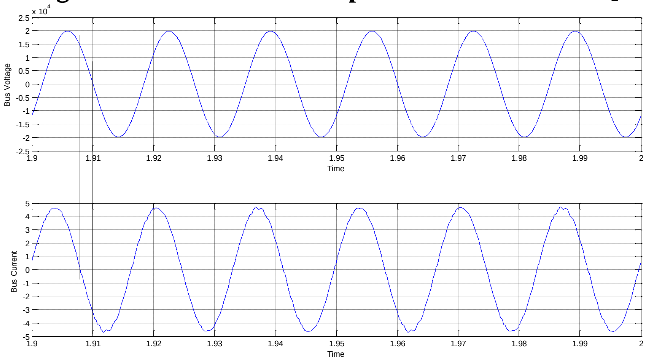

Fig. 13. Voltage and current waveforms in case of 100% Q

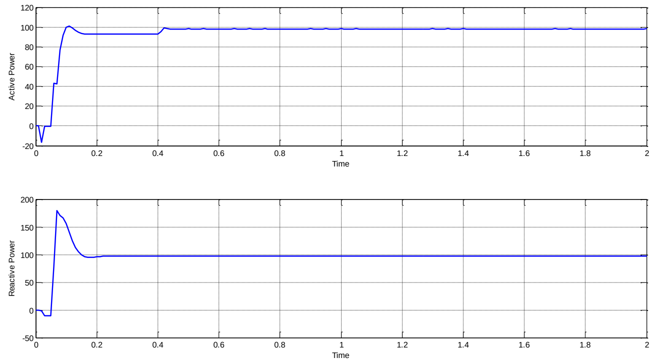

Figure 14. Active and reactive power in case of 100% Q

The results in Fig. 13 presents a greater phase shift angle that reaches about 45^{o}. Also, Fig. 14 indicates the increase in reactive power to be near 100 kVAR.

To ensure the robustness of the controller, another parameter is tested which is the irradiance value. A certain change in irradiance is applied at the instant t = 1 sec. The value is reduced from 1000 w/m^2 to be 800 W/m^2. After that, it increase again at t = 1.7 sec. the simulation is performed at the case of 20% reactive power compensation level. The controller response is fast and it is illustrated in Fig. 15. Both the active and reactive power are reduced with the same percentage when the irradiance is decreased. Moreover, they are restored to their initial values when the irradiance is increased again.

V. CONCLUSIONS

The control of photovoltaic systems has a great concern in recent year as these types of generation systems are rapidly increased among the whole world. The phase locked loop control is considered one of the most reliable control techniques due its applicability in power systems application. In this research, a grid connected photovoltaic system is modeled and simulated through MATLAB/SIMULINK package. The phase locked loop (PLL) control algorithm is designed and built up to provide a reactive power flow control in order to improve the power quality of the electrical network. The results are extracted at different levels of reactive power compensation. The results introduced a great effectiveness of the used control approach. Moreover, the effect of changing operating parameters such as irradiance is studied. The results referred to a fast response of the controller to such changes.

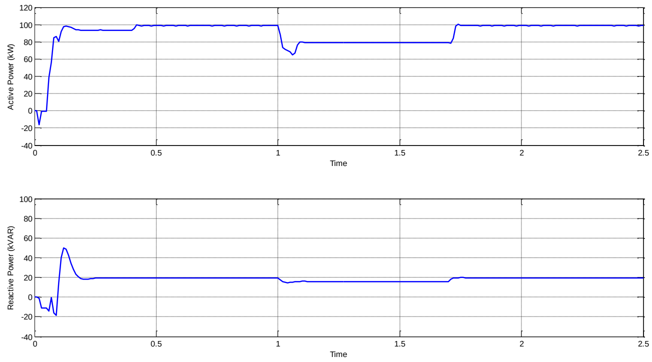

Fig.15. P and Q variation including a change in irradiance

REFERENCES

1. REN 21, Global Status Report, 2019.
2. Z Chang and S Tao ,"Power Quality Analysis of PhotovoltaicGeneration Integrated in User-Side Grid", International Journal ofComputer and Electrical Engineering, Vol. 5, No. 2, April 2013.
3. B. Singh, D. T. Shahani, and A. K. Verma, "Neural network controlled grid interfaced solar photovoltaic power generation,"IET Power Electron., pp.614–626, Mar. 2014
4. R. Kumar Agarwal and ,B.Singh, "LMF based control algorithm for single stage three phase grid integrated SPS system", IEEE Trans.Sustain.Energy,,pp.1379-1387,apr. 2016.
5. S.A.George and F.M.Chacko,"Comparison of different control methods for integrated system of MPPT powered PV module and STATCOM," in Proc. Int. Conf. Renew. Energy Sustain. Energy,Dec,.2013
6. D. T. Shahani and B. Singh, "IRPT based control of a 50 kW grid interfaced solar photovoltaic power generating system with power quality improvement,"inProc.IEEE4th Int.Symp.PowerElectron. Distrib. Gener. Syst.,July. 2013
7. Keerthena Das M. S., Soumya Sathyan, "Comparison of Control Methods For Single Stage3-Phase Grid Connected PV System" Proceedings of the International Conference on Inventive Research in Computing Applications (ICIRCA 2018)
8. Mahmoud M. Hussein, "Control of a Grid Connected PV Inverter for Supplying Powers with Different Power Factors", 2018 Twentieth International Middle East Power Systems Conference (MEPCON), Cairo University, Egypt
9. Savitha PB, Shashikala MS, PuttaBuddhi KL, "Modeling of Photovoltaic Array and Control of Grid Connected Photovoltaic System to Provide Quality Power to Grid", 2016 International Conference on Electrical, Electronics, Communication, Computer and Optimization Techniques (ICEECCOT)
10. Nourhan M. Elbehairy, Rania A. Swief, Amr M. Abdin, T. S. Abdelsalam, "Maximum Power Point Tracking For a Stand Alone PV System Under Shading Conditions Using Flower Pollination Algorithm", 2019 Twenty first International Middle East Power Systems Conference (MEPCON), Tanta University, Egypt
11. M. G. Villalva, J. R Gazoli and E. R. Filho, "Comprehensive approach to modeling and simulation of photovoltaic arrays," *IEEE Trans. Pow. Elec.*, vol.24, no.5, pp.1198-1208, May 2009.
12. Juergen Roeber, Christian Zwick, Andreas Baenisch, Simon Dirauf, Guenter Roppenecker and Robert Weigel, "Novel Control Methods for Phase Lock Loops", 2015 European Conference on Circuit Theory and Design (ECCTD)

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