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Reduced THD and Improved Line Regulation for a Standalone MG applying Optimized Fractional Order PID Controller

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Abstract – The work is based on improving the line regulation and minimizing the THD for the inverter voltage at the connected bus to the microgrid (MG). These objectives have been verified in this study under operating conditions with different types of loads disturbances. The control technique for THD minimization and voltage regulation enhancement is obtained using the tripled actions controller (TAC). This controller combines a PR (Proportional Resonant) controller with SHC (Secondary/Secondary Hybrid Control) and introduces a third controller for the PWM of the voltage obtained from the inverter. Voltage regulation is adjusted applying the FOPID controller, so the bus voltage and the operating frequency will be restored at their rated values. To verify the optimization for this objectives, the study employed PSO method to find the optimum solution. Comparison is done with previous published work, which illustrated that the proposed system outperformed the others with respect to voltage waveform, frequency deviation, and THD. Also, the developed control technique verifies improved power quality issues (PQ) and increased the reliability of power system when supplying different load types.

Keywords: Voltage Regulation, Standalone MG, Total Harmonic Distortion, Tripled Actions Controller, Optimized Methodology.

I. Introduction

The occurred harmonics in any power network represent a PQ problem in this power system and they lead to another impacts such as conductor overheating, increased hysteresis losses, eddy current, and overheating in electrical machines. as well as increase neutral current, zero sequence current, trip in circuit breaker, communications interference, equipment malfunction, inaccurate sensors measurements, and reduction lifetime of equipment [1]. MG's infrastructure uses the technique of distributed generation (DG). Many benefits of DG include power losses reduction and voltage profile improvement due to the integration of DG micro-sources near to load centers and increased efficiency. Generally, the **PQ** problems such as the deviation of voltage / frequency, poor power factor, THD due to inverter connected and natural loads has now become of paramount importance
[2].The definition of power quality is the ability of network to operate at the rated voltage and frequency [3]. In power systems, especially MG, harmonics are a key PQ issue. Harmonics have serious consequences for the electrical power network. The negative consequences include an increase in the cost, which represent in the losses in transformers (copper, iron, and stray losses), heating on neutral cables, heating of transformers circuit breakers tripping, malfunction of capacitor bank panel in electromagnetic equipment for all equipment's power factor improvement [4–5].

The non-linear loads connected to any network lead to occurrence of harmonics because the waveforms are not pure sine curve [5]. The filters are one of solutions for minimizing these harmonics based on supplying negative selected values [6-7]. While there are some disadvantages of filters such as they need larger place, and they may also resonant with the actual connected load [8-9]. In islanded mode of MG, the application of PR-controller to reduce harmonics and adjust both values of voltage and current from the VSI [10]. Applying the PR control for islanded mode can verifying the load demanded power [11, 12] within acceptable voltage deviation of ±5% and acceptable frequency deviation of ± 0.5 % of their rated values [13-14]. A secondary controller loop and virtual impedance control approach are used for restoring the permissible voltage / frequency deviation with improved results and reliable operation of the proposed technique. SHC control includes a synchronization loop for a smooth transition among grid connected and isolated mode [10].

Verifying minimization of the voltage harmonics can be obtained using the introduced feed-forward of current loop to PR controller, that lead to regulate the magnitude of output voltage and its transient curve. With this proposed technique selective harmonic compensator are implemented as a tripled actions controller (TAC) [15]. The optimized parameters of proposed TAC would improve the PQ requirements [16]. Moreover, to adjust the magnitude of voltage at the rated value it has been achieved using FOPID controller. FOPID is getting a lot of popularity due to its potential to outperform PID controller. It has the greatest ability due to the existence of to two additional parameters of μ and λ. As well as, the proportional and integral already existed [17]. This article is organized as, the 1st Section gives the introduction. 2nd Section addressed the operation of islanded MG inverter. 3rd Section presents the types of applied MG controllers. 4th Section explains the proposed criteria. 5th Section discuss the outputs. While the last one introduces the recommendations.

II. Islanded mode VSI Controller

For obtaining better operation of islanded MG, it is important selecting the appropriate controller. The PR controller is commonly applied for this objective [18] and also functions effectively of THD of a 3-Φ VSI. The PR controller is used for closed loops of voltage and current. The system's three closed loops comprise the PR controller as the first loop, a SHC as the second loop, and a feedforward current controller as the third loop. The PR controller transfer functions for these loops in Eq. (1) [10], while Fig. 1 shows these control loops [16]:

$$G_{v\&i}(s) = K_{P_{v\&i}} + \frac{K_{R_{v\&i}} s}{s^2 + 2\omega_{c_{v\&i}} s + \omega_o^2} + \sum_{h=5,7,11,..} \frac{K_{h_{v\&i}} s}{s^2 + 2(h\omega_{c_{v\&i}})s + (h\omega_o)^2} \quad (1)$$

While v & i *are* voltage and current; $K_{P_{v\&i}}$ and $K_{R_{v\&i}}$ are proportional gains; $K_{h_{v\&i}}$ is the gain for harmonic; $\omega_{c_{\&,i}}$ is the bandwidth at the harmonic; $\omega_{o,}$ h the base frequency and harmonic number.

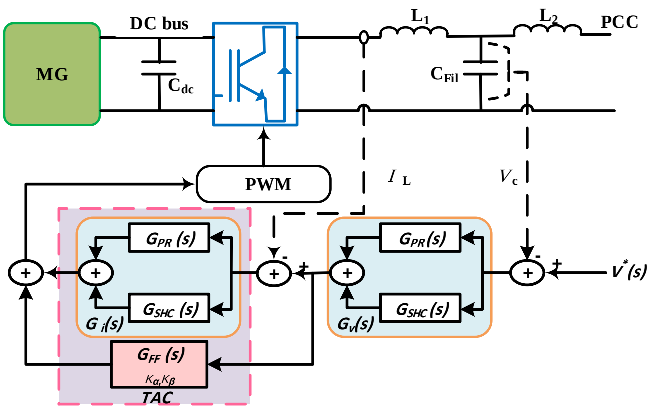

Fig.1 B.D of VSI.

III. Modeling of Islanded mode MG

PR Control

Applying PR control to MG leads to adjust the values of load real and imaginary power [10, 19]. Also, the objectives of PR control are allocation of power between the MG connected supplies. that actually make the system more reliable. The PR control operate based on Eq. (2), Eq. (3) for frequency and voltage:

$$\omega_{dp} = \omega_{ref.} + G_P(s)\Delta P \quad (2)$$

$$E_{dp} = E_{ref.} + G_Q(s)\Delta Q \quad (3)$$

While: ω_{dp} & E_{dp} are the frequency and the magnitude of voltage, $\omega_{ref.}$ & $E_{ref.}$ are the rated values of both of frequency and the magnitude of voltage, ΔP & ΔQ *are the* power deviations between the reference and actual values, and $G_p(s)$ and $G_Q(s)$ are the TF for both powers.

For obtaining improved allocation between the inverters, the coupling between the droop and virtual impedance is preferred. The equations describe the operation of virtual impedance are given in Eq. (4) and Eq. (5) [10]:

$$v_{v\_imp\,\propto} = R_{v\_imp}\, i_{o\propto} + \omega\, L_{v\_imp}\, i_{o\beta} \quad (4)$$

$$v_{v\_imp\,\beta} = R_{v\_imp}\, i_{o\beta} + \omega\, L_{v\_imp}\, i_{o\propto} \quad (5)$$

While R_{v_imp} and L_{v_imp} are the virtual values of R and L, $v_{v\_imp\,\propto\beta}$ and $i_{\alpha\beta}$ are the voltage and current in ∝ β coordinate.

Adjustment Control

The adjustment control depends on the change in the magnitude of voltage and the frequency obtained by PR controller. The operation of this controller presented as equations (6) and (7) [24]:

$$\omega_{rst} = K_{pF}\,\Delta\omega + K_{iF}\int \Delta\omega\, dt \quad (6)$$

$$E_{rst} = K_{pE}\,\Delta E + K_{iE}\int \Delta E dt \quad (7)$$

While: ω_{rst} & E_{rst} are the frequency and voltage related to second., $\Delta\omega$ & ΔE are the change in them :

$\Delta\omega = (\omega_{ref} - \omega_{act})$,

$\Delta E = (E_{ref.} - E_{act})$,

Synchronism of MG

Operation in synchronism is required when the MG is connected to electrical grid. But in isolated mode, three-phase voltage are generated as a reference of MG. The synchronized frequency ω_{synch} of the inverter is used for correcting the gain of PR controller as: [10]

$$\omega_{synch} = (v_{g\beta}\, v_{c\propto} - v_{g\propto}\, v_{c\beta})\, G_{LPF}\, \frac{K_{p\,synch} s + K_{i\,synch}}{s} \quad (8)$$

While, $G_{LPF} = \frac{\omega_c}{s+\omega_c}$, $K_{p\,synch}$, $K_{i\,synch}$ are the gains of synchronization loop control.

Figure 2 illustrate the schematic diagram of islanded MG proposed technique.

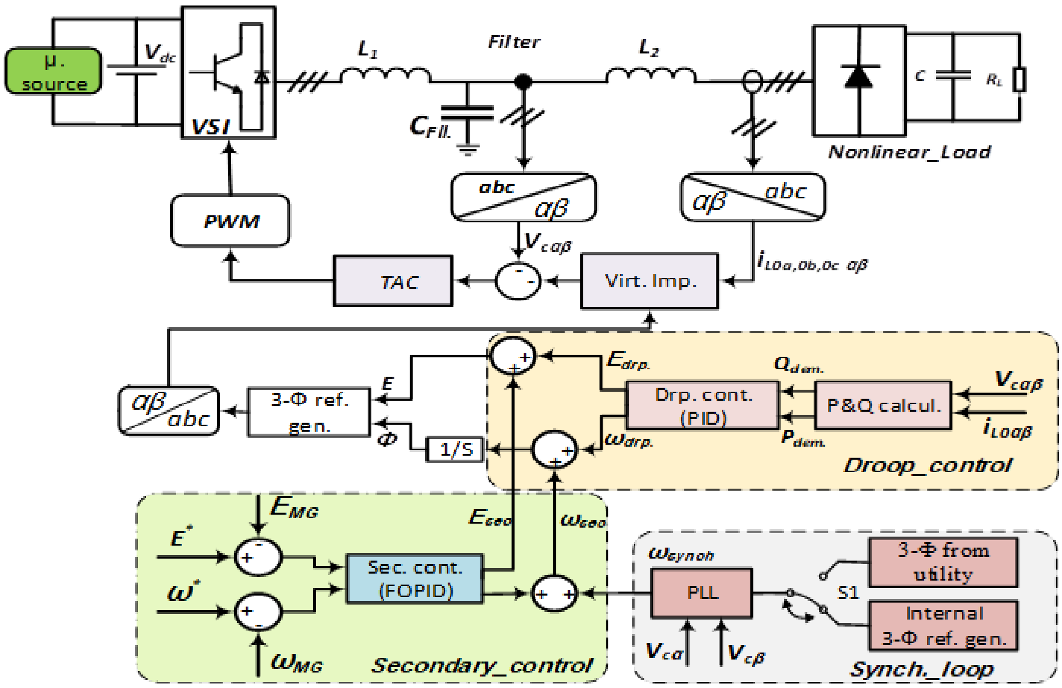

Fig. 2 B.D for islanded MG in αβ-coordinates.

IV. Calculation of Optimized-FOPID

PID controllers are applied with large scale for control systems. There are other techniques applied for any control process, but the PID controller is commonly used due to its easy adjustment and its simple operation. Appearance of fractional calculus has simplified the move toward the transients. So, TF of FOPID controllers have been presented. The FOPID consists of three parallel elements [20]. To operate the system under the required response, then applying accurate methods to find the best values [21]. The FOPID controller is given by:

$$C(s) = K_p + K_i s^{-\lambda} + K_d s^{\mu} \qquad (9)$$

While λ and μ are fractions. they have value between (0 to 2) [22].

The PSO optimization methodology characterized by limited parameters, lower sensitivity to the cost function, simple, does not depend on the initial particle and has two acceleration coefficients and generate very good dynamic performance [23].

The cost function (F_{Total}) is selected to be a combination of the THD and voltage regulation, that would be minimized related to the IEEE standard [13].This function is given in Eq. (10) to verify that; reduce the maximum overshoot, undershoot, the error in the voltage and also reduce the THD in both of voltage and current.

$$F_{Total} = THD_v + (e_\alpha/e_\beta) * \gamma + (\Delta e_\alpha/\Delta e_\beta) * \delta + \left(\frac{1}{T}\int_0^T e_{sf}^2\, dt + \frac{1}{T}\int_0^T e_{sv}^2\, dt\right) * \varepsilon \qquad (10)$$

while

THD_v	Voltage THD
e_α	α voltage error
e_β	β voltage error
Δe_α	α voltage error dev.
Δe_β	β voltage error dev.
e_{sf}^2	Squared frequency error
e_{sv}^2	Squared voltage error
γ, δ and ε	Coeff.”s related to objectives

V. The Operation of Standalone MG with Different Loads

The rated power of MG inverter is 2.2kW. The loading conditions are divided into three stages, which are nonlinear, nonlinear in parallel with linear loads and finally linear load only each of loading is operated for duration of 0.3 sec. Fig. 3-a, and Fig. 3-b illustrate the reference load powers. These values are of 900W and 100VAR for duration of 0.3 sec. Then the linear load is connected with the previous load for interval 0.3 sec. that is 1100W and 400VAR. The last interval the nonlinear load is disconnected.

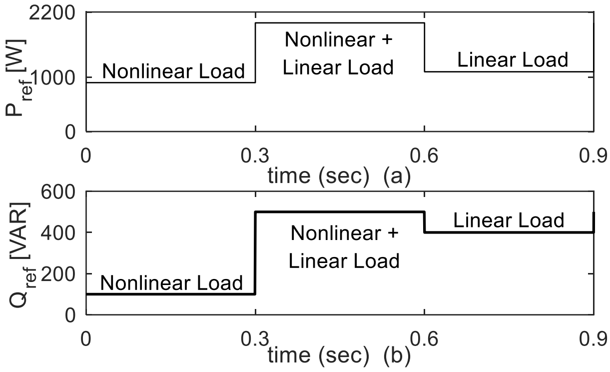

Fig.3 Base load real /imaginary power

Fig. 4 shows the output voltage and showing clearly what happened at the instant of load switching From this figure the output voltage is kept constant although the changing in load conditions and switching occurrence, while Fig. 5 illustrates the output current and showing clearly what happened at the instant of changing loading conditions, it is clear that the current profile changes according to the load switching without occurring of any spikes.

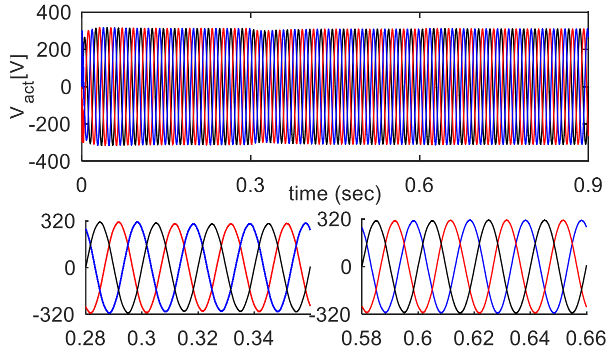

Fig.4 VSI voltage

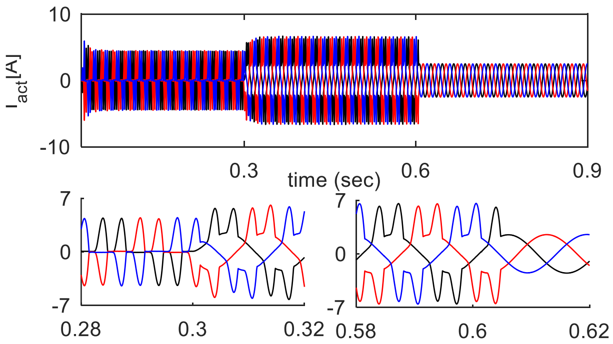

Fig.5 VSI current.

Fig. 6-a Depicts the frequency of PR controller, which is related to the load active power. The large value of frequency dev. is 0.1 Hz. Fig. 6-b shows the frequency with FOPID controller that leads to minimize the frequency dev. and its dynamic response. The frequency is returned to its rated value after 0.2 sec. where the overshoot and undershoot are of ± 0.015Hz.

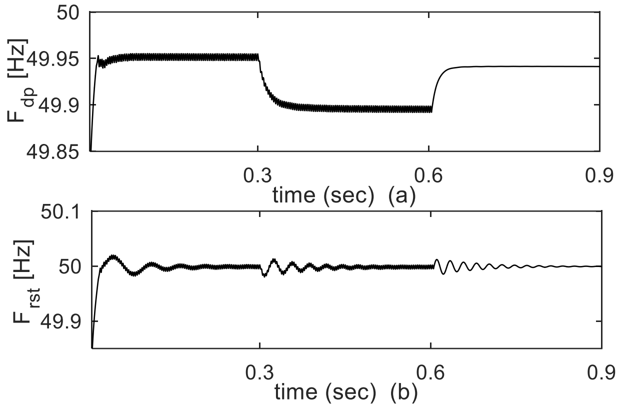

Fig.6 frequency response due to droop and second control (a) F_{droop}. (b) F_{second}..

Fig. 7-a shows magnitude of voltage due to droop control. The voltage changes directly to imaginary power demanded. The large value of this deviation is of 12V. But Fig. 7-b illustrates the magnitude of voltage due to FOPID control. That leads to improve the voltage level, where the large value of this deviation is of 5V.

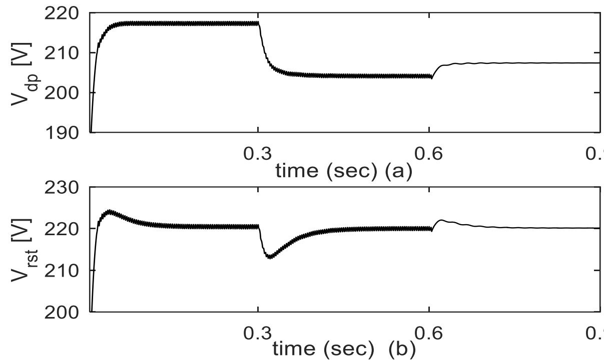

Fig.7 droop and secondary voltage (a)V_{droop} (b) V_{second}.

Fig. 8-a, and Fig. 8-b depict the supplied real and imaginary power. The power output from inverter are the same as the load demanded power. Fig.9 illustrates the voltage error between the ref. voltage and the inverter voltage of the same phase, this curve shows how the output of inverter is synchronized with the ref. voltage.

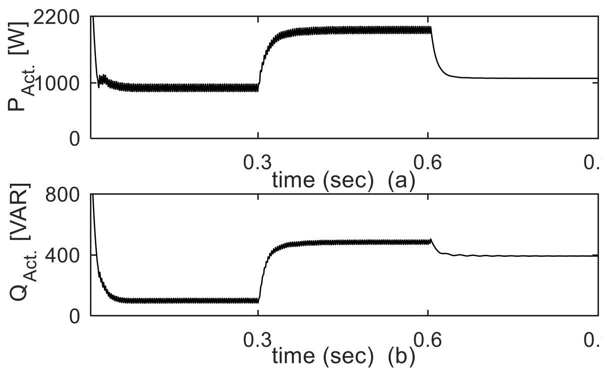

Fig. 8 the o/p power (a) $P_{act.}$ (b) $Q_{act.}$

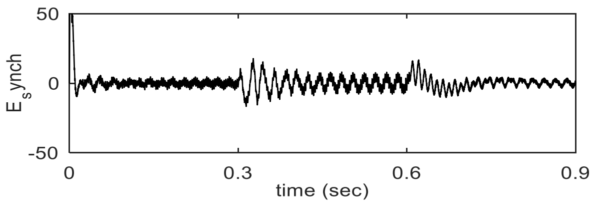

Fig. 9 Voltage error from the rated and the obtained voltage of the same phase.

The different harmonics of the obtained voltage are analyzed from 3rd order to 15th orders as cleared in table 1. The 3rd values and the other multiple of it are eliminated. But there is a negative sequence having a minimum value due to the occurrence of nonlinear load that generates harmonics.

Table 1 Percentage of different harmonics due to different loads

Harmonic Ord.	Linear ld	Non-linear ld	Linear + Non-linear ld
third	.0	.01	.02
fifth	.02	.23	.8
seventh	.01	.35	.95
ninth	.00	.00	.01
elventh	..01	.09	.17
13 th	0.01	0.07	0.16
15th	0.00	0.00	0.00
Harmonic number	Linear load	Nonlinear load	Linear + Nonlinear loads
third	0.0	0.01	0.02
fifth	0.02	0.23	0.8
seventh	0.01	0.35	0.95
ninth	0.00	0.00	0.01
eleventh	0.01	0.09	0.17
13th	0.01	0.07	0.16
15th	0.00	0.00	0.00

VI. Conclusion

The power quality issues have been improved applying TAC using optimized FOPID. TAC verifies minimized THD of output voltage, this THD has a value lower than the IEEE standard limits. In addition to the voltage and frequency regulation is improved for all types of loading conditions. For the optimization technique it must take into account the constraints to be verified and to obtain high dynamic performance. The comparison is done between the proposed technique with the published work, that shows the superiority of the proposed methodology.

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