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AUTONOMOUS PV RESIDENTIAL SYSTEMS DESIGN BASED ON OPTIMAL METHOD FOR POWER QUALITY IMPROVEMENT

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Abstract*: – It is truth that photovoltaic (PV) systems are secure energy sources, clean and environment friendly, so the installation of PV systems has been increasing nowadays. But capital costs and unreliable operations are main drawbacks for a standalone residential PV system. However, to avoid compatibility problems, to get uninterrupted power supply, less expected failure rate, economic and efficient operation, it is necessary to design residential PV standalone systems with power quality parameters with in national and worldwide benchmarks. This paper presents design of autonomous PV residential systems with improved power quality. To this course, important parameters of autonomous PV systems are legitimately decided. Besides these there is an outline methodology that reaches demanded standards and enhances power quality also. At long last an optimization algorithm composed using swarm intelligence techniques. The methodical results are substantiated by extensive simulation and understanding negotiations are given illustrating efficiency of our planned system.*

Key Words: photovoltaic (PV), sinusoidal pulse width modulation.

1 .INTRODUCTION

PV systems are most promising technologies of renewable energy sources. Nowadays most of remote areas (islands, rural territories, etc.) are supplied by their own installation of residential PV systems, because of increased electrical costs from suppliers and increased technologies in conversion of solar energy to electrical energy. So consumers are interested installing PV systems. Now these investments are subsidized and encouraged where transmission and distribution works are difficult to developed.

Proper designing of autonomous PV residential systems and their PQ parameters with national and world wide benchmarks is an important matter. from other benefits these systems will give uninterrupted power supply, avoid compatibility problems, and moderate operational cost for long time. Here power indices must satisfy the demands of national and worldwide standards and at the same time her we have to avoid the extreme equipment dimensioning and designs.

From existing technical literature power quality concepts in standalone PV systems is discussed by two different methods, the first one as designing the energy storage unit through improved load demand management[1]-[4] and second one as controlling the supply voltage through the adaptation of sophisticated control loops [5]-[7]. Outputs of above mentioned works are saying that high power quality can obtained in standalone application even under highly distorted and unbalanced loads. in our work if we select design parameter of system arbitrarily, we will not guarantee to power quality. But selecting these parameters in methodological way can provide high power quality in standalone systems under steady state. But this concept is only small scale installations.

To this work we present new methodology based artificial intelligent for design purpose. By finding and giving the correct values to critical variables of standalone systems, it is possible to power quality with in limitations. For this work we are applying this methodology to typical power levels like 20kw and 50kw of standalone PV systems.

2. SYSTEM DETAILED ANALYSIS

2.1 System Configuration

The main elements of system under study are shown in fig.1.

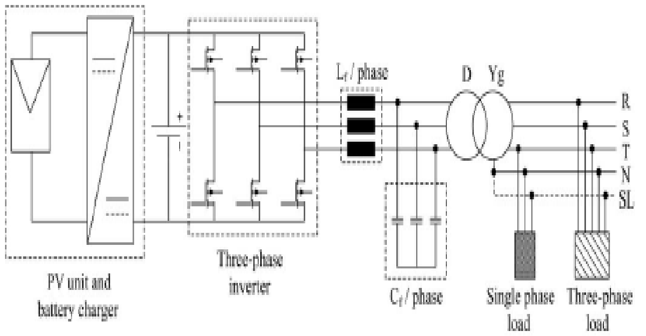

Fig1. Configuration of System under Study (SL is ground conductor)

The battery bank is charged by a PV unit through a series charger, the 3- phase inverter is supplied by battery bank. The above shown configuration is the most common type for standalone PV residential units. There are some sophisticated energy storage systems which are proposed in [2]-[4]. But for our study the actual selection energy storage is not need, because our main target is optimal selection of design parameters of harmonic filter, inverter and transformer. Here it is assumed that inverter input voltage is constant even though battery bank nominal DC voltage is variable in this work

Coming to inverter topology, the most common commercial inverter for residential application is the classical 3-phase full bridge inverter topology. There are some various multi-level inverter topologies [8] in autonomous micro grids having many advantages like efficiency and power density. We can select various types, it is not a limit so for our methodology any inverter topology voltage transfer function is important.

Coming to transformer, the transformer turns ratio may affect the dc voltage level, because the load voltage depends on its value and their relations are studied as

$$\sqrt{\frac{3}{2}} * ma * \frac{Vdc}{2} \qquad (1)$$

$$\overline{V}_{1N}=\overline{V}_{inv,N} - \Delta\overline{V}_{Lf} \qquad (2)$$

$$V_{2N}=\sqrt{3}\frac{V1N}{n} \qquad (3)$$

Where ma is the amplitude modulation ratio of the SPWM controller; Vdc is the DC voltage at the inverter dc side; V_{1N} ,V_{2N} are the transformer line to line nominal primary, secondary voltages(rms) respectively; ΔVLf is the voltage drop at filter inductance(rms value); n is the transformer turns ratio.

Eq.(1)-(3) are derived by SPWM inverter principles[9]. The bar indicators in (2) are phasor quantities. The transformer secondary side is Ygd (grounded star) connected, in order to provide high voltages on load sided and to provide path for zero sequence currents so load voltage free from asymmetry due zero sequence currents absent. Load voltage also free from 3rd order harmonics.

Next one is filter; it consists of inductor capacitor bank. It is used to cutoff the lower order harmonics that are generated by nonlinear loads and higher order harmonics by the SPWM technique of inverter. The resonance frequency (ωr) of filter is given by

$$\omega r=\frac{1}{\sqrt{(LfCf)}} \qquad (4)$$

Where Lf, Cf are inductance, capacitance of filter per phase respectively.

ωr can be selected up to 3rd order harmonics because ωr may not deal with the fifth order harmonic component efficiently. Furthermore inductor of filter also restricts short circuit current level with in acceptance level of safe operation of inverter. $I_{inv,SC}$ is the 3-phase short circuit current of inverter, and is given by formula:

$$I_{inv,sc}=\frac{Vinv,N}{\sqrt{3}.\omega b.Lf} \qquad (5)$$

Where $V_{inv,N}$ is inverter line to line nominal rms value; ωb is the load voltage angular frequency.

Actually $I_{inv,sc}$ has to be higher than rated current of inverter, else protection scheme would have poor selectivity. Generally modern inverters of PV applications can withstand up to 280% of nominal current for few seconds time. It is functional use inverter whose rated power is equal to residential peak burdens. if we go for high rated inverter the short circuit current value increases which leads increase of cost and worsens the utilization factor of inverter. In this project the design procedure doesn't depend upon inverter control loop, since it aims to obtain a power quality optimization under steady state condition of system.

2.2 Definitions of design criteria

There are some parameters of system are whose values are to be set to meet power quality targets and safe and economical operation conditions. The parameters are summarized as follows:

a) Asymmetry due to Single Phase Loads (asym): According to [10],[11] it is defined as ratio of negative sequence voltage component to positive voltage component. We should have to get the asym within limits given by national and international standards (IEC, NEMA, and IEEE) [12]-[15] even under worst load case.

$$\text{asym}=\frac{V2}{V1}*100 \qquad (6)$$

Where V_2 is the negative sequence component of voltage at load side (rms value); V_1 is the positive sequence component of voltage at load side (rms value) .

b) Total Harmonic distortion due to Nonlinear loads (THD_V): It is an important parameter. It gives overall harmonic content in the system. Symmetrical component analysis is used to calculate the harmonic distortion of load voltage. it is also within limits imposed by [16] even in worst case.

c) Inverter Short Circuit Current Ratio (sci): It is defined as follows

$$\text{sci}=\frac{Iinv{,}SC}{Iinv{,}N} \qquad (7)$$

Where sci denotes the short circuit current that both the inverter and inductor have to withstand
Where $I_{inv,N}$ is the inverter nominal rms current.

d) Inverter Nominal Power Ratio(scs): It is defined as follows:

$$\text{scs}=\frac{Sinv{,}N}{SL{,}N} \qquad (8)$$

Where $S_{inv,N}=\sqrt{3}*V_{inv,N}*I_{inv,N}$; $S_{L,N}=\sqrt{3}*V_{2N}*I_{2N}$
Where $S_{inv,N}$ is the inverter nominal apparent power .
$S_{L,N}$ = load nominal apparent power.
Where scs defines the necessary inverter over dimension in order to meet the power targets and safe economic operation restrictions. It is a techno-ecological factor.

e) Inverter Nominal Current ratio (nomi): it is defined as follows:

$$\text{nomi}=\frac{Iinv{,}N}{I1N} \qquad (9)$$

$$\text{Where } \bar{I}_{1N}=\bar{I}_{inv,N}+\bar{I}cf \qquad (10)$$

I_{1N} is the nominal current of transformer at primary winding (rms value) Icf is the filter capacitor current value(rms).The bar in the eq.(10) represents phasor relationship. Here the factor nomi denotes the limitable capacitive current in circuit. It is being restriction for finding of Lf and Cf values properly.

3. ASYMMETRY ANALYSIS

By taking single phase loads from three phase supply, produce the different current ratings on three phases which will cause load voltage asymmetry. We used a, b, c pointers for phases identification and 1, 2, 0 pointer for current and voltage sequence components. The equivalent sequential circuit for single phase loading by symmetrical component analysis is shown in fig. 2.

The singe phase load conditions of system are

$$\bar{I}a=\bar{V}a/\overline{ZL};,\ \bar{I}b=\bar{I}c=0 \qquad (11)$$

Where Ia, Ib, Ic are phase currents. Va is the phase a voltage, Z_L is the load impedance. Substituting above values in symmetrical component matrix and by analyzing we get the relation that is

$$\bar{I}1=\bar{I}2=\bar{I}0=\frac{\bar{I}a}{3} \qquad (12)$$

I1, I2, I0 are positive, negative and zero sequence components of current respectively.

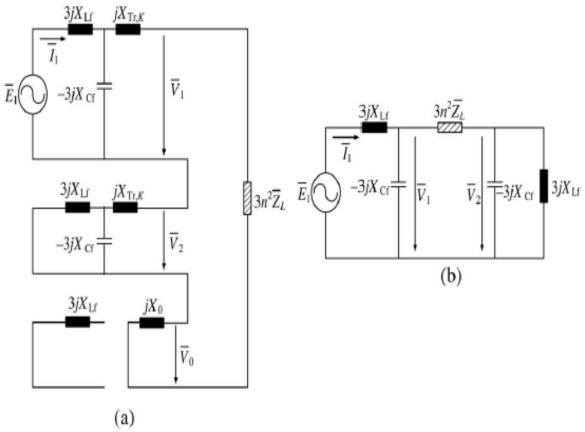

Fig.2 Equivalent sequential circuit for single phase loading. (a) Initial circuit and (b). Simplified circuit for $X_{Tr,K} = X_0 = 0$

From fig.2.(a) X_{Lf} is the filter inductance impedance at load voltage frequency, X_{cf} is the filter capacitor impedance at load voltage frequency, $X_{Tr,k}$ is the shot circuit impedance of transformer, X_0 is the zero sequence (ground) impedance.

The circuit fig. 2(a) is normalized to primary voltage level and the filter inductance and capacitance are transformed to their equivalent delta connection phase values. Fig. 2(b) shows simplified circuit of fig.2 (a) by assuming that both zero sequence impedance and short circuit impedance equal to zero. The E_1 indicates the symmetrical three phase voltage under steady state condition because of SPWM control technique. Her E_1 means PV generator, battery bank, and inverter combination representation. From phasor analysis of fig.2 (b) gives the following expression for representing asymmetry in single phase loads

$$Asym = [\{1 + \frac{f^2-1}{q} * \tan[\arccos(pf)]\}^2 + \{\frac{f^2-1}{q}\}^2\}]^{-1/2} \quad (13)$$

$f=\frac{fr}{fb}$; $q=\frac{Xcf}{RL*n^2}$ where fr, fb filter resonant frequency and load voltage frequency respectively, f and q called as frequency and impedance ratios respectively. Power factor is denoted as pf, and R_L is the load impedance real part.

By observing the eq.13 we can say that asymmetry of voltage of the circuit depending upon variables f, q, and pf. here the power factor is displacement power factor because loads are nonlinear type.

4. HARMONIC ANALYSIS

We know that the presence of nonlinear loads cause the harmonic distortion. In this analysis we are taking three phase nonlinear loads, because they have high shock on load voltage.

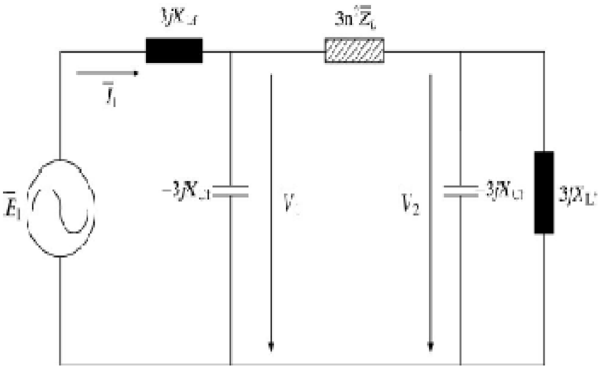

Fig.3 Equivalent sequence circuit for harmonic analysis: three-phase loading, normalized to the secondary transformer windings voltage level.

Fig. 3 circuit is used for analysis of each singe load current harmonic component. Now we are going to replace the index i through harmonic order.

From the analyzing the circuit is shown in fig.3 we will get following relation for three phase loading.

$$Z_{2.i}=3n^{-2} * \frac{Xcf}{[i-\frac{1}{i}(\frac{fr}{fb})^2} \quad (14)$$

$$V_{i(TP)}=V_{2,i}=I_i*Z_{2,i} \quad (15)$$

Where $Z_{2,i}$ is the negative system impedance for the ith order load current harmonic component. Ii is the rms value of the ith order load current harmonic component (per phase). $V_{i(TP)}$ is the rms value of the ith order load voltage harmonic component (three-phase loading)

The THD_V was found by following equation .it is derived from eq.(15).

$$THDv=\frac{1}{vb}*\{\sum_{i=3,5,..} Vi(TP)^2\}^2 \quad (16)$$

Where vb is the fundamental component of voltage at load side (rms value); assume vb is equal to V_{2N} (transformer line to line nominal secondary voltage (rms value).

5. OPTIMIZATION METHOD

Because of more number of variables and parameters of this system, we are going for optimization techniques. The main aim of optimization method is to adjust important of variables of proposed system. Since these variables f, q, n, ma,(amplitude modulation ratio of SPWM controller) and Vdc (DC voltage at inverter dc side) affect the design parameters of system which are explained in section 2. The parameters asym, THDv, sci, scs, and nomi must obey limits of Table 1.

TABLE1. Parameters limitations

Parameter	Limit (%)	Parameter	Limit
asym	<5	scs	<2
THDv	<8	nomi	<1.5
		sci	<5

To get good power quality and safe operation of system, we should follow the limits. NEMA and IEC standards have given limits for asym and THDv. The limit selection for scs, nomi, and sci is based on the techno economical criteria. Because of non linearity, large number, and complexity of derived equations we are going for PSO (particle swarm optimization based on swarm intelligence. It is simple and easily completed. In order to adjust our parameters f, q, n, and Vdc, we have to minimize our optimization function

$$f(k)=\frac{asym}{w1}+\frac{t5}{w2}+\frac{t7}{w3}+\frac{t11}{w4}+\frac{sci}{w5}+\frac{scs}{w6}+\frac{nomi}{w7} \quad (17)$$

Where w1,2,...7 are weight factors are set to upper limit of table.1 for normalizing design parameters. and where t5, t7, t11 are maximum permissible harmonic component. They are computed as follows using X nonlinear loads

$$ti=\frac{X.Zi.Ii}{230} \qquad (18)$$

Where i=5, 7, 11. The weight factors take following values w1=0.05, w2=0.06, w3=0.05, w4=0.035, w5=5, w6=2, and w7=1.5 according to table.1. And k is a column vector containing the variables k1, K2, k3, k4.

$$K=[k1, k2, k3, k4]^{T}=[f, q. n, Vdc]^{T}. \qquad (19)$$

Lastly, the range of variables in column vector k are defined as f=2-4, q=0.1-10, and n=0.5-10

Vdc={ 100<Vdc<300

300< Vdc<600

600<Vdc<800}

Here the both Vdc and ma are variables different from other two. The range of these values is decided by designer and by technical restrictions. Example ma has to set to lower than one otherwise over modulation takes place and for commercial inverter in standalone systems Vdc is between 100 and 800V. To solve eq. 17 not only pso, any mathematical tool can be used.

6. SIMULATION RESULTS

The discussed design example is considering two autonomous installations with maximum load power of 20kw and 50kw respectively. Assume the power factor for both cases is equal to 0.85. X set to 9 for both cases, indicating that load is highly distorted. Consider Vdc varies between 300 and 600 for simple reasons and ma is set to 0.5. Following power quality table.1, the final selection of 20-KW PV installation is f=2.0762 q= 0.199, n=0.712 and vdc=400.16. and sci=4.0478, scs=1.65 and nomi=1.180 Thus, the values of technical parameters are Lf=0.43mH, Cf=5.4mF, $S_{inv,N}$=33KVA and V_{1N}=160. Similarly, the final selection of 50-KW PV installation is f=2.0158, q=0.2250, n=0.785 and Vdc=500. And sci=4.551, scs=1.267 and nomi=1.42. Thus, values of technical parameters are Lf=0.22mH, Cf=9.9mF, Sinv,N=75KVA and V_{1N}=180.

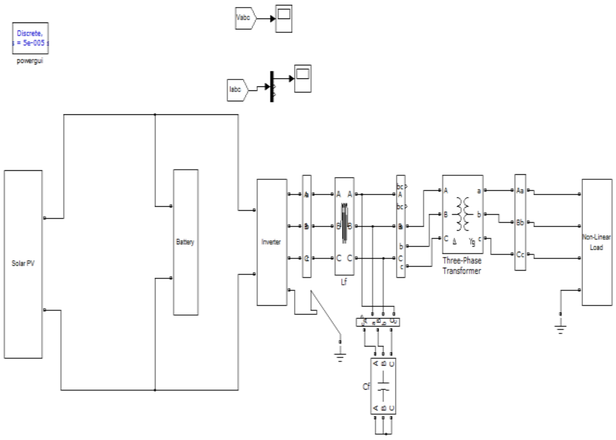

Fig3.simulink block model of system with nonlinear load

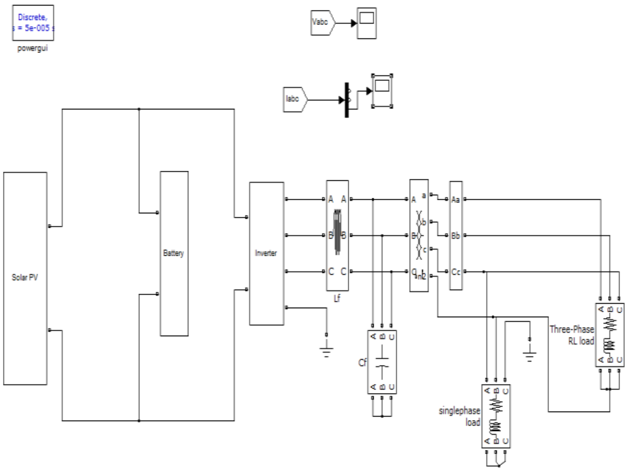

Fig4.simulink block model of system with nonlinear load

Fig.3and fig.4 shows the block diagram of the Simulink model and includes all the sub circuits that are shown in fig. 1, namely the three-phase inverter (using IGBTs/diodes as switching elements); the SPWM controller (20 kHz carrier frequency); the three-phase transformer (Ygd1, short-circuit impedance 4%); the filter elements (three-phase inductor and capacitor); the photovoltaic generator, which has been simulated as a single voltage controlled current source [17], the battery charger, which has been simulated as a series dc/dc converter (PWM buck topology) in continuous conduction mode, and the battery bank (nickel–metal–hydride).

Table II presents some selected simulation results for the cases of 20- and 50-kW applications. Additionally, the load voltage and current waveforms for the 50-kW case with maximum produced harmonic distortion and asymmetry are shown in figs. 4 and 5, respectively. It is noted that the distorted load consists of a three-phase diode rectifier with filter capacitor.

These simulation results highlight the fact that the selection of system design parameters according to the proposed design method restricts load voltage unbalance and harmonic distortion within the limits of the international standards, even for extremely nonlinear loads. Moreover, these selected results (as well as many similar simulation results that have been obtained for various power levels and for various nonlinear load profiles) corroborate the analytical results.

TABLE II
MATLAB/Simulink Selected Simulation Results

Test	Asym(i)		Asym(ii)	
	Sim(**)	Theor (**)	sim(**)	Theor(**)
Single phas Loading at $P_{N/3}$(*)	5.375%	5.13%	5.45%	5.14%
	THDv(i)		THDv(ii)	
Three phase nonlinear load	Sim(**)	Theor(**)	sim(**)	Theor(**)
	3.47%	3.59%	1.92%	1.87%

**sim, simulation result; Theor, Theoretical calculation *load power factor for both case asummed to 0.85 and X is set io 9.

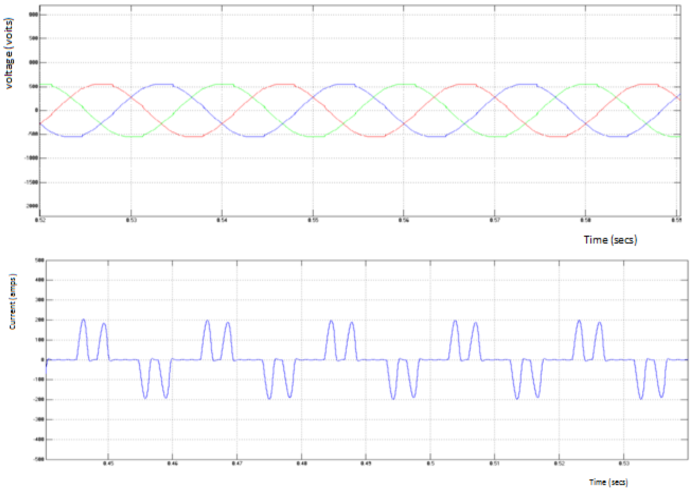

Fig.5. Load voltages waveforms (upper case) and load current waveform of one line (lower case) for 50kw three phase diode rectifier with 3-mF smoothing capacitor ; the THD$_v$ value is 1.919%..

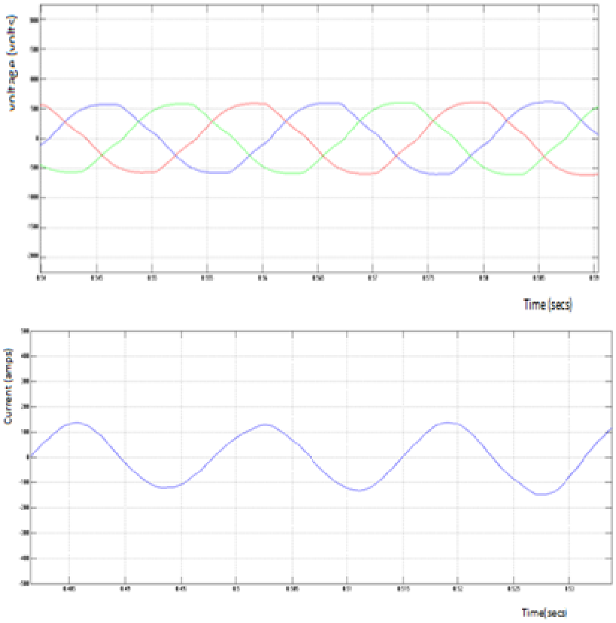

Fig.6. Load voltage waveform (upper case) and load current waveform of one line (lower case) for 17-kw single phase load; the asym value is 5.455%;

7. CONCLUSION

The power quality improvement through design of standalone residential PV system with help of optimum method is has been discussed in this paper. Circuit analysis which is developed in this paper has shown that power quality nature of standalone PV residential systems is strongly dependent on the alteration of important factors that must be suitably chose keeping in mind the end goal, to meet consistence with international power quality standards. The results of present paper confirm the fittingness of proposed design methodology and demonstrate that good power quality of supply in 3-phase autonomous PV residential application is a realistic target, depending on initial design.

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