Investigation of Resonant Frequencies and Quality Factors of RLC Loads in the Residential Electrical Environment

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INTRODUCTION

The effectiveness of an inverter's anti-islanding algorithms is highly dependent upon the resonant frequency and quality (Q) factor of the load with which the inverter is connected under an island condition. If the resonant frequency of the load is outside of the over and under frequency trip setpoint window (59.3 to 60.5 Hz for a UL1741 compliant inverter), the inverter will be unable to maintain the island, and will trip off line on a frequency fault [1]. In the rare case where the resonant frequency of the islanded load is within this window, and the active part of the load closely matches the active power output of the inverter, the Q factor of the resonant circuit has a significant effect on the ability of the circuit to remain in stable resonance [2].

The purpose of the investigation is to identify the type of residential loads which could contribute to the creation of the conditions necessary for the formation of an islanding, and to quantify the expected resonant frequencies and Q factors created by the presence of these loads.

HOUSEHOLD ELECTRICAL LOAD CHARACTERISTICS

The electric load of a residence may be reduced to the parallel RLC circuit described in IEEE 929 [3] and UL 1741 [4]. Most residential loads are resistive in nature (heating appliances, incandescent lighting, et. al.), and do not provide a significant contribution to the lumped inductance and capacitance of the RLC circuit. The notable exceptions are the inductive loads presented by single-phase induction motors used in pumps, blowers, fans and other household appliances. The winding leakage impedances of these motors can result in a significant lumped inductance. While household capacitive loads are uncommon, and power factor correction is normally implemented at medium voltage rather than at the residential service level, starting and running capacitors associated with these single-phase motors will interact with the inductive portion of the load to produce a resonance at some frequency.

A survey of data from a number of appliance manufacturers and appliance motor manufacturers [5, 6] shows that these motors are typically in the 1/6 to 1 hp range, and consist of either split phase (Figure 1), shaded pole, capacitor start (Figure 2) or permanent split capacitor (PSC) types (Figure 3).

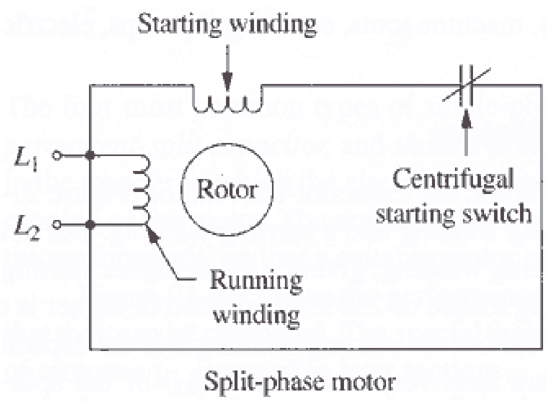

Figure 1

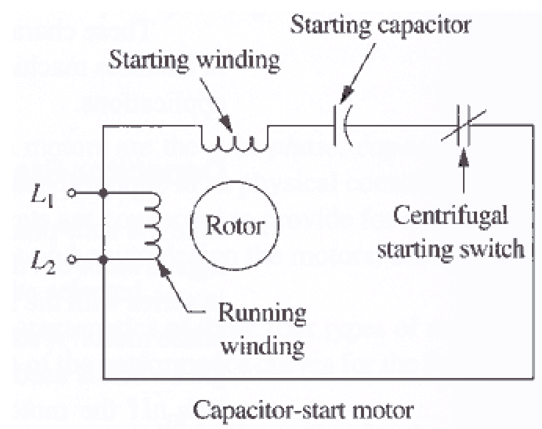

Figure 2

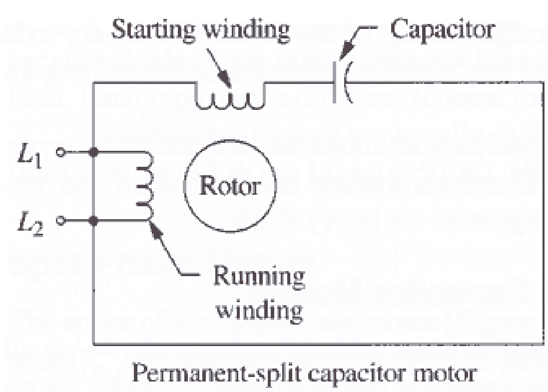

Figure 3

The split phase and shaded pole designs do not require start or run capacitors. Starting capacitors for motors that utilize them are large (e.g., 300 µF for a ½ hp motor), but are removed from the circuit by a centrifugal switch within a second or so of starting, while running capacitors used in PSC motors are smaller (~ 40 µF for a ½ hp motor) [7].

As the PSC run capacitors are the only types that remain in the equivalent RLC circuit for a period of time exceeding the IEEE 929 anti-islanding trip times (two seconds), the determination of an equivalent lumped capacitance for the residential load is limited to the run capacitors associated with these motors. Capacitor values are readily available for these motors, as is overall power factor, from manufacturer's data sheets. However, since the values of leakage inductance for the running and starting windings are not readily available, a precise reduction of the motor to an equivalent parallel RLC circuit is not possible. However, by assuming that the start winding leakage inductance is negligible, the circuit can be easily reduced. This assumption is conservative in that it will tend to result in a lower (i.e., closer to 60 Hz) resonant frequency since the start winding inductance reduces the "effective" capacitance of the start circuit, driving C higher, and, therefore, the resonant frequency lower.

SAMPLE CALCULATION OF RESONANT FREQUENCY AND Q FACTOR

The two parameters of interest are the resonant frequency, f_0 of the RLC circuit,

$$f_0 \equiv \frac{1}{2\pi\sqrt{L_1 C_1}}$$

and its quality factor, Q.

$$Q = R^* \sqrt{C/L} \text{ or } Vars/Watts.$$

Horsepower and run capacitor value for various household appliances are tabulated in Appendix A. In general, worst case resonance conditions (i.e, low resonant frequency and high Q) will result from assuming the highest possible value of capacitance. As an example, assume a summer load with simultaneous operation in a residence of a central air conditioning compressor, furnace blower, pool filter pump, well pump, washing machine and refrigerator, per the tabulation of Appendix A. Further, assume that start winding inductance of the PSC motor may be neglected so that the motor may be reduced to an equivalent RLC circuit. R, L and C may then be calculated as follows:

Appliance	Load (HP)	Efficiency (1)	Load (W)	PF(1)	Var	R (ohm)	C (F)	L (H)	f_0 (Hz)	Q
Furnace Blower Motor	1	0.7	1066	0.9	516	13.5	2.50E-05	0.058597		
Central AC Condensor Fan Motor	1	0.7	1066	0.9	516	13.5	2.50E-05	0.058597		
Pool Filter Pump Motor	0.75	0.7	799	0.9	387	18.0	2.00E-05	0.077059		
Well Pump Motor	0.75	0.7	799	0.9	387	18.0	2.30E-05	0.074608		
Washing Machine Motor	0.5	0.7	533	0.9	258	27.0	1.45E-05	0.113415		
Refrigerator Motor	0.25	0.7	266	0.9	129	54.0	8.00E-07	0.286378		
Other Loads (2)			514	1		28.0				
Total (in Parallel)			5044		2194	2.9	1.08E-04	0.0137	131	0.25

(1) Refer to motor electrical data from Reference 7; efficiency and PF values selected at ends of range to create lowest resonant frequency and highest Q.

(2) Other resistive loads selected to match 5500 VA inverter rated output.

CONCLUSIONS

In order to create a 60 Hz resonant circuit, it is necessary to capacitively compensate for the inductive reactance of the entire residential motor load. Appliance motor manufacturers' data suggest that this is not standard practice. Typical run capacitors and power factors for PSC motors for residential appliances result in resonant frequencies in the 100 to 200 Hz range.

REFERENCES

1. M. Begovic, M. Ropp, A. Rohatgi, A. Pregelj, "Determining the Sufficiency of Standard Protective Relaying for Islanding Prevention in Grid Connected PV Systems", Proceedings of the 2nd World Conference and Exhibition on Photovoltaic Solar Energy Conversion, Vienna, Austria, July 1998.

2. J. Stevens, Sandia Report SAND 2000-1938, August 2000, "Development and Testing of an Approach to Anti-Islanding in Utility-Interconnected Photovoltaic Systems".

3. IEEE 929-2000, *Recommended Practice for Utility Interface of Photovoltaic (PV) Systems.*

4. UL Standard 1741, *Inverters, Converters and Controllers for Use in Independent Power Systems.*

5. K. Heinecke, "Single Phase Electric Motors, Characteristics and Applications," www.iprocessmart.com/leeson/leeson_motor.

6. Marathon Electric, Single Phase PSC Motor Data Sheets, www.marathonelectric.com.

7. Seacor, Inc., Westwood, NJ, Motor Capacitor Technical Data, www.seacorinc.com.

8. M. Ropp, R. Bonn, C. Whitaker, S. Gonzalez, Sandia Smart Anti-Islanding Project, Task II, *Investigation of the Impact of Single-Phase Induction Machines in Island Loads*, unpublished report.

APPENDICES

A. Typical Household Appliance Motor Loads

Application	*Description*	*H.P.*	*Mfd*	*@ VAC*	*source*
	Heating				
Heating	Snyder/Arco Heat Pump Motor	0.10	5	370	1
Heatpump AC	Marathon in-line Condensor Motor	0.50	10	370	1
Heating	York Furnace Blower Motor	1.00	25	370	1
Heating	Lennox Furnace Blower Motor	0.75	15	370	1
	Air Conditioning				
Window AC	Westinghouse AC motor	0.33	7.5	370	1
Window AC	York AC Motor	0.50	7.5	370	1
Window AC	York Condenser Fan Motor	0.20	5	370	1
Rooftop AC	Trane/GE Condenser Motor	0.20	4	370	1
Central AC	Fedders A/C Condenser and Evaporator Mtr	0.33	7.5	370	1
Central AC	Fedders/Westinghouse Package unit Mtr	0.75	10	370	1
Central AC	Carrier Condenser Fan Motor	1.00	25	370	1
Central AC	AO Smith Condenser Fan Motor	0.80	20	370	1
	Pool, Spa				
Pool	Filter Pump Motor	2.00	30		5
Pool	Heater Motor	0.50	5	370	6
Pool	Pump Motor	0.75	20	370	6
Pool	Booster Motor	0.50	5	370	6
	Well and Sump				
Sump	Sump Pump Motor	0.33	5	370	6
Well Pump	Well Pump Motor Start	0.75	86		2
Well Pump	Well Pump Motor Run	0.75	23		2
	Household Appliances				
Washing Machine	Washing Machine Motor	0.50	14.5	420	3
Dryer	Spin Dryer Motor	0.25	split		1
Diswasher	Motor	n/a	split		1
Convection Oven	Blower motor	n/a	split		1
Refrigerator	Condenser Motor	0.25	0.8	400	3
Ceiling Fan	Motor	n/a	4	250	4
Garage	Door Opener Motor	0.33	50		7

Sources:

1 Johnstone supply catalog
2 Franklin Electric
3 www.kme.panasonic.co.jp
4 NTE Electronics
5 http://www.poolcenter.com/motor_parts.htm
6 Fasco OEM Direct
7 www.jwsgaragedoor.com/genieparts.htm