ANALYSIS AND DESIGN OF A PARALLEL RESONANT NETWORK POWER SUPPLY FOR A RAPID CYCLING SYNCHROTRON

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Abstract

Rapid Cycling Synchrotron (RCS) requires dc biased sinusoidal excitation for electromagnets. Power supplies based on resonant schemes are best suited for such applications, as only the losses of the resonant network are drawn from the mains and the magnets are energized by resonating its inductance with external energy storage elements. In this paper study of various options for powering the magnets and its excitation source is carried out. Optimization of network elements for parallel resonant network with respect to the operating and investment cost is carried out. Tolerance analysis of a high-*Q* resonant network with respect to variation in component values and its effect on amplitude and phase of magnet current, and the ac component reflected in the magnet current due to presence of ac and dc input source ripple is documented. Design of a parallel, continuous ac excited resonant network for the QF2 magnet for the proposed 1 GeV RCS is presented.

INTRODUCTION

A spallation neutron source which is an important tool for research in material science, life science, chemistry, fundamental and nuclear physics, earth and environment science is proposed at RRCAT. It mainly consists of a 1 GeV, 25 Hz RCS for production of high energy protons and a target which is bombarded with these protons to produce neutrons. This paper describes the analysis and design of a powering scheme for a family of quadrupole magnets of the proposed RCS. The requirements of a power supply for these electromagnets are quite different from conventional dc power supplies [1]. A method where the energy of the magnets, which is needed only for a short time during each period, can be stored is preferred. Therefore oscillatory circuits are used where the energy is stored in the capacitors and only the losses of the resonant network are drawn from the mains. A string of magnets energized with a single source develops a very high voltage with respect to ground. To overcome this problem, the circuit elements are connected in a configuration called White circuit [2]. The objective of this paper is to present a systematic approach for selection of circuit topology, to carry out tolerance analysis of the resonant network and finally to recommend a powering scheme for QF2 magnets.

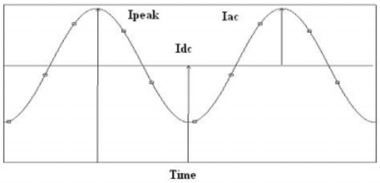

Figure 1: A dc biased sinusoidal current wave for excitation of RCS magnets.

SCHEMES

General specifications of the QF2 magnet are summarized in Table 1. The excitation frequency is 25 Hz and the peak current is 1230 A. Typical waveform of a dc biased sinusoidal current is shown in Fig. 1. I_{ac} is the peak current of the ac component and I_{dc} is the average current in the magnet. Parallel and series resonance circuits (PRC and SRC, respectively) are best suited for such applications. The PRC and SRC schemes are shown in Fig. 2. The comparison between PRC and SRC is as follows:

Table 1: Specifications of QF2 Magnet

Total Numbers	:8
I_{dc}	:1230 A
$I_{ac\ Peak}$	:730 A
I_{pk}	:1960 A
Inductance/magnet	:11 mH
Peak energy/magnet	:11kJ
DC resistance/Magnet	:2 mΩ
Resonant Frequency	:25 Hz

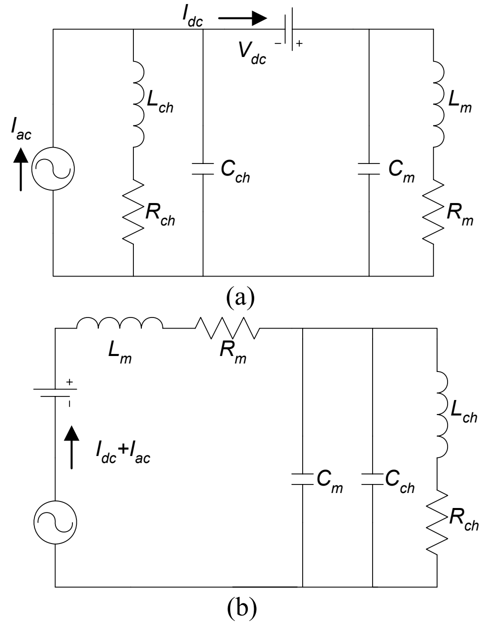

Figure 2: Resonant excitation schemes: (a) PRC (b) SRC.

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In PRC two separate sources are required while in SRC the ac and dc source can be generated with a single power source. The current in SRC is directly driven in the magnet, while in the PRC the current is fed in the choke and is not directly fed to the magnet. PRC system is operated at low power as the peak power drawn during a cycle in SRC is more, while there is less variation in power drawn by PRC.

Further, the ac source can be either a continuous or a pulsed source. Continuous source is preferred as the pulsed sources lead to high percentage of harmonic component in magnet current and the waveform manipulations, in case of magnet saturation, is not possible in pulsed sources. In pulsed sources, an average dc current flows in the primary choke winding causing additional loss in primary winding of coupling transformer.

COST OPTIMIZATION OF PRC

The magnet current I_m (see fig. 1) can be expressed as:

$$I_m = I_{dc} - I_{ac}\cos wt \qquad (1)$$

The current in the resonating choke L_{ch} is,

$$I_{ch} = I_{dc}(1 - m\alpha\cos wt) \qquad (2)$$

where, $\alpha = (I_{ac}/I_{dc})$ and $m = (L_m/L_{ch})$. L_m is the total magnet inductance. The resonant frequency of the parallel resonant network is,

$$f = \frac{1}{2\pi}\sqrt{\frac{L_{ch}+L_m}{L_{ch}L_m(C_{ch}+C_m)}} \qquad (3)$$

C_m and C_{ch} are the magnet and choke resonating capacitance, respectively. An index for the size of the choke in QF2 powering network can be computed as follows:

$$L_{opt\_function} = 1/2 * Lch * Irms * Ipk \qquad (4)$$

The choke investment cost (L_{ic}) normalized to the average stored energy in the magnet can be derived as:

$$\frac{L_{ic}}{0.5L_mI_{dc}^2} = \frac{0.376(1+m\alpha)C_l}{m}\sqrt{1+\alpha^2m^2/2} \qquad (5)$$

C_l is the cost of transformer equivalent of the choke in Rs/kVA. The normalized choke operational cost, L_{oc} which depends on the Q factor of the choke (Q_{ch}) is:

$$\frac{L_{oc}}{0.5L_mI_{dc}^2} = \frac{\left(2+\alpha^2m^2\right)C_oN\omega_0}{1000mQ_{ch}} \qquad (6)$$

where, N is the total operation time in hours, C_o is the electricity consumption rate in Rs/kWh, and,

$$Q_m = \frac{\omega_o L_m}{R_m} \qquad Q_{ch} = \frac{\omega_o L_{ch}}{R_{ch}} \qquad (7)$$

Similarly the normalized capacitor investment (C_{ic}) and the operational (C_{oc}) cost can be derived as,

$$\frac{C_{ic}}{0.5L_mI_{dc}^2} = \frac{\alpha^2 m\omega_o C_c}{1000} \qquad (8)$$

$$\frac{C_{oc}}{0.5L_mI_{dc}^2} = \frac{2m\omega_0\beta C_0N}{10^6} \qquad (9)$$

where, C_c is the cost of capacitor in Rs/kVAr, β is the loss factor of the capacitor in watts/kVAr.

Equations 5 through 9 are used for optimization of network. It can be seen that the total operating cost is minimum for a specific value of *m* .This is the optimum value of *m*. For the case of QF2 magnets, optimum value of *m* is 1.9. The maximum limit of *m* is decided by the ratio α, which is the limit for discontinuous current in the choke, the maximum limit for *m* is therefore 1/α. The optimum *m* is also a function of the quality factor However, this dependence is not very strong and for all practical purposes the optimum value for *m* can be taken as 1.5. Figure 3 shows the detailed cost break-up of QF2 magnet resonant network.

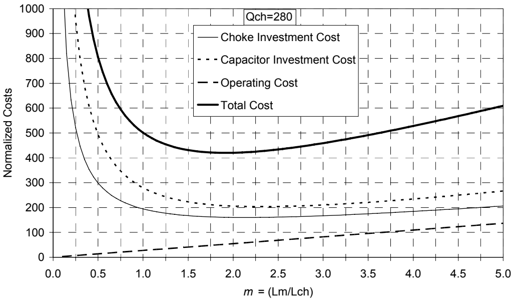


Figure 3: The cost break-up for QF2 as a function of *m*.

SOURCE HARMONICS AND TOLERENCE ANALYSIS

A high-*Q* resonant tuned circuit basically behaves like a band pass filter and dominantly passes the resonant frequency and attenuates significantly other frequencies present in the network. The ac and dc sources used in PRC are not ideal and contain unwanted frequency components. The expression for the ratio of the magnet current to the dc source current for calculating the allowable ripple current in the source is,

$$\left(\frac{I_m}{I_s}\right)_{dcsource} = \frac{1}{\left(1-\omega_n^{\,2}+j\dfrac{\omega_n}{Q_m}\right)} \quad \text{where } \omega_n = \frac{\omega}{\omega_o} \qquad (10)$$

Similarly, the expression for the ratio of the magnet current to the ac source current for calculating the allowable harmonics in the ac source is expressed as:

$$\left(\frac{I_m}{I_s}\right)_{acsource} = \frac{\left(q+j\omega_{nQ_m}\right)}{(m+q)-\omega_n^{\,2}(1+m)(1+q)+j\omega_n(1+m)\left(Q_m+\dfrac{q}{Q_m}-\omega_n^{\,2}Q_m\right)} \qquad (11)$$

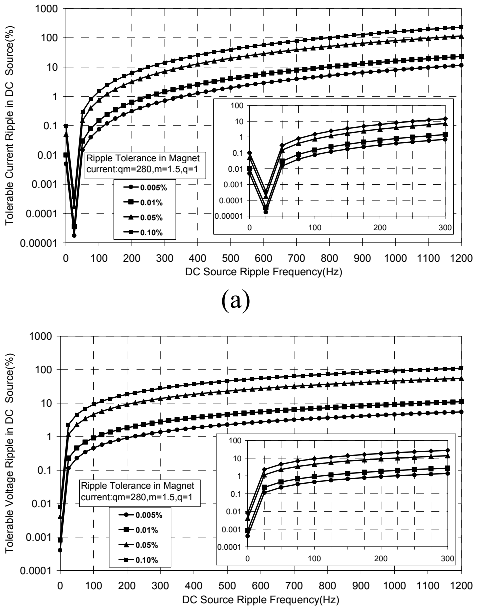
where $q = (Q_m/Q_{ch})$.The phase angle Φ in degrees, between the source and the magnet current can be calculated as follows,

$$\Phi = \tan^{-1}\frac{\omega_nQ_m}{q} - \tan^{-1}\left(\frac{\omega_n(1+m)\left(Q_m+\dfrac{q}{Q_m}-\omega_n^{\,2}Q_m\right)}{(m+q)-\omega_n^{\,2}(1+m)(1+q)}\right) - 180 \qquad (12)$$

Various plots showing allowable per cent ripple in the dc current and voltage as a function of ripple frequency for QF2 network with specified allowable tolerance in magnet current and tolerable harmonic level in the ac source as a function of harmonic frequency for different specified tolerable variations in the magnet current can be generated using (10)-(12). Figure 5 shows the allowable per cent ripple in the dc source current and voltage as a function of its ripple frequency for QF2 network with specified allowable tolerance in magnet current.

All passive components in PRC are subjected to variations due to manufacturing tolerances, aging, drift, temperature variations etc. All these variations results in change in the resonant frequency and/or *Q* which changes the gain and phase characteristics.

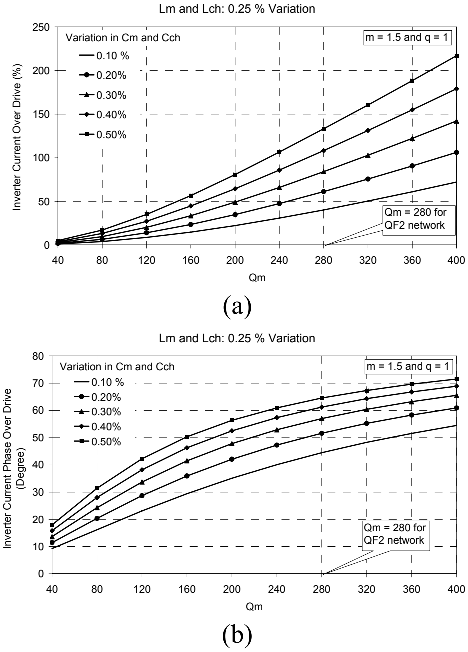
Figure 6 shows inverter current amplitude overdrive and phase overdrive for 0.25% variation in L_m and L_{ch}. Detailed analysis of the effects of component tolerances is reported in [3].



(a)

(b)

Figure 5: Allowable ripple in the dc source (a) current, and, (b) voltage with respect to ripple frequency for QF2.



(a)

(b)

Figure 6: Inverter current (a) amplitude overdrive, and, (b) phase overdrive for 0.25% variation in L_m and L_{ch}.

Based on the above discussion the following recommendations are made for the powering scheme of QF2 magnet for the proposed RCS at RRCAT.

1) QF2 magnets should be energized with a single mesh, parallel resonant network powering scheme, excited by an ac excitation of continuous type.

2) Limits for ac and dc source harmonics for the QF2 network are as follows:

- Maximum tolerable 300 Hz current and voltage ripple in dc source for 0.01 % ripple in the magnet current is 0.8% and 3% respectively.
- Maximum tolerable 50 Hz current ripple in ac source for 0.01 % ripple in the magnet current is 10 %.

3) To limit the inverter amplitude overdrive to a reasonable 50% and phase to 45 degree, the tolerance in value of capacitances should be below 0.1%, and the inductances should be designed so that the tolerance in their values is below 0.25%.

CONCLUSION

A systematic approach to select a powering scheme for QF2 type quadrupole magnet for a 25 Hz, 1 GeV RCS is demonstrated. A single mesh parallel resonant network with a continuous ac excitation is deemed suitable for the purpose of powering all the 8 magnets in series. PRC is chosen and continuous ac source is preferred. The effect of variations and tolerances in the component values were reflected in graphical form. Also the effect of dc source voltage and current ripple components and ac source harmonics and its effect on output magnet current were studied. The ratings of the resonant network element and the power requirement of ac and dc source for QF2 magnet network were finalized. The study shows that to limit the current overdrive of the ac source of QF2 network to a lower level (50%), the tolerances in inductance should be as tight as 0.25% and the tolerance in resonating capacitors should be limited to 0.1%.

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