ISBN: 978-3-95450-208-0 doi:10.18429/JACoW-IPAC2019-MOPRB057

AN APPROACH TO ALLEVIATING HEAVY BEAM LOADING EFFECT ON THE SYNCHROTRON MACHINE THROUGH THE EXISTED LOW LEVEL RF FEEDBACK SYSTEM

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Abstract

To pursue the highest brightness and intensity of the synchrotron light, the synchrotron machines are pushed to operate with as high as possible of the beam current. To suppress the heavy beam loading effects, the direct RF feedback is currently widely used. This paper provides an another approach to alleviating the heavy beam loading effects on machine operation. Different from the direct RF feedback technique, this approach need not add additional feedback loop to the existed RF feedback system. Applying a proper angle rotation to the I-Q error signals of the cavity voltage, before entering the existed feedback loop, is the only action required in this approach. The paper will explain the working mechanism and investigate the behaviour of this approach, through an example case, with numerical simulation.

INTRODUCTION

With beam current, the cavity voltage contains RF fields, generated by the RF power source and induced by the beam current. It is the beam-induced RF field that causes so-called beam loading effects in the machine operation. The effect can make machine difficult in keeping a constant cavity voltage, stable high current operation, etc. Currently, the direct RF feedback and detuned cavity are the common adopted approaches to alleviating heavy beam loading effect in machine operation.

Different from the direct RF feedback, the presented approach need not implant any additional RF feedback loop to the existed RF system. Applying a proper angle rotation to the feedback I-Q errors of the controlled cavity voltage before the error signals enters the RF feedback loop is the only action required in this approach.

The working mechanism of this approach is explained by examining the change of RF matching condition of an RF cavity, that is caused by beam loading. the behaviour of this approach is also investigated by numerical simulation, through an example case. All the formulas used in the numerical simulation is presented.

WORKING MECHANISM FOR THIS APPROACH

To understand the working mechanism for this approach, we first examine what an RF cavity will change as operating with beam current. To obtain maximum power transfer under operation with beam current, the load impedance of the RF cavity is set to keep RF matching condition with the waveguide or the coaxial line, so-called transmission line. To understand how to keep RF matching condition, let us examine the change, caused by beam current, in the normalized load impedance, which is equal to the load impedance divided by the characteristic impedance of the transmission line. The characteristic impedance of the transmission line can be defined from the power loss of a RF load, and will not be changed after it is defined. Let us define the cavity voltage as the load voltage for an RF cavity which is on resonance and without beam-loading. Then the power loss on the RF load can be described by the cavity voltage (v_c) and cavity shunt impedance (R_s):

$$p_c = \frac{v_c^2}{2 \cdot R_s} \tag{1}$$

The impedance of the cavity load, Z_c, is then equal to R_s. Under such definition for the load impedance, the transmission line impedance Z_t can be represented by [1]:

$$Z_t = R_s / \beta \tag{2}$$

where β is the coupling parameter of the RF cavity. While cavity is detuned and without beam loading, the cavity impedance can be written as [2]:

$$Z_c = \frac{1}{Y_c} = \frac{R_s}{1 - j 2 Q_0 \delta} \tag{3}$$

where $\delta = (\omega_c - \omega_{RF}) / \omega_{RF}$. While the RF cavity is loaded with beam current, the admittance of the cavity load includes the RF-harmonic beam current [3]:

$$Y_c = \frac{1}{Z_c} = \frac{1 - j 2 Q_0 \delta}{R_s} + \frac{i_b}{v_c} \cdot \exp(-j \phi_s) \tag{4}$$

where ϕ_s is the phase difference between the RF-harmonic beam current (i_b) and the cavity voltage (v_c). ϕ_s is equal to the synchronous phase in synchrotron machines. The reflection coefficient for the RF cavity is then equal to

$$\Gamma = \frac{(Z_c / Z_t) - 1}{(Z_c / Z_t) - 1} = \frac{(Z_c \cdot \beta / R_s) - 1}{(Z_c \cdot \beta / R_s) + 1} \tag{5}$$

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It demands that the imaginary part in Eq. (4) must be zero for RF matching; it means that the RF cavity is detuned by

$$\delta=-\frac{i_b\cdot R_s}{2Q_0 v_c}\cdot\sin(\phi_s) \tag{6}$$

As the cavity frequency is detuned to that in Eq. (6), we will say the RF cavity is on RF compensation condition. The total cavity voltage $\boldsymbol{v}_c$ is made up by the superposition of voltage components $\boldsymbol{v}_g$ and $\boldsymbol{v}_b$, which are produced by the RF generator current $\boldsymbol{i}_g$, and the RF-harmonic beam current $\boldsymbol{i}_b$ respectively [2]:

$$\boldsymbol{v}_c=\boldsymbol{v}_b+\boldsymbol{v}_g=(\boldsymbol{i}_b+\boldsymbol{i}_g)\cdot\frac{R_s}{1+\beta}\cdot\cos(\psi)\cdot e^{j\psi} \tag{7}$$

where ψ, called the cavity tuning angle, is defined by

$$\tan(\psi)=2\cdot Q_L\cdot\delta \tag{8}$$

The steady phasor diagram of the RF generator current $\boldsymbol{i}_g$ and the RF-harmonic beam current $\boldsymbol{i}_b$ on the RF compensation condition is shown in Fig. 1. While the impedance of the cavity load is real, the RF generator current $\boldsymbol{i}_g$, the cavity voltage $\boldsymbol{v}_c$ and the incident RF wave are all in phase. As shown in Fig. 1 and described by Eq. (7), we know a phase difference ψ is between $\boldsymbol{i}_c$ and $\boldsymbol{v}_c$, and the same phase difference is between $\boldsymbol{i}_g$ and $\boldsymbol{v}_g$. In RF feedback system, we pick up $\boldsymbol{v}_c$ signal, generating a feedback error $\delta\boldsymbol{v}_c$. The error $\delta\boldsymbol{v}_c$ is used to correct the incident RF wave, equivalent to correcting $\boldsymbol{i}_g$ in Fig. 1. As beam current becomes greater, the detuned cavity frequency become greater; the phase difference between the feedback error $\delta\boldsymbol{v}_c$ and the correction $\delta\boldsymbol{v}_g$ also becomes greater. This increasing phase difference can make the RF feedback system more difficult to correct the error $\delta\boldsymbol{v}_c$ and maintain a constant cavity voltage.

If an angle rotation is applied to the I-Q components of $\delta\boldsymbol{v}_c$ before $\delta\boldsymbol{v}_c$ enters the existed RF feedback loop, the phase difference between the feedback error $\delta\boldsymbol{v}_c$ and the correction $\delta\boldsymbol{v}_g$ will changes. A proper angle rotation should be able to help the RF feedback system to keep machine in stable condition under heavy beam loading operation. It is this observation that inspires us to do this study. It is also the working mechanism of this approach.

FORMULAE FOR SIMULATION

In the simulation, $\boldsymbol{v}_g$ is given by Eq. (7) – induced by $\boldsymbol{i}_g$. and the I-Q components of $\boldsymbol{i}_g$ is given by Eq. (14). Because of the synchrotron motion of the beam bunches, $\boldsymbol{v}_b$ will not be as $\boldsymbol{v}_g$, given by Eq. (7), and instead is calculated by the superposition of the field voltage which is excited by each beam bunch passing through the cavity. In the calculation a beam bunch is presented as a macro

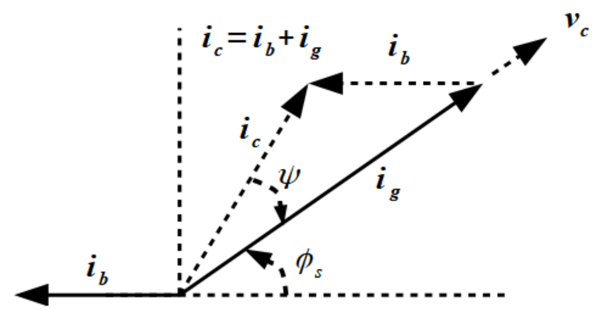

Figure 1: Steady state phasor diagram of the RF generator current and the RF-harmonic beam current on RF compensation condition.

charge particle. As the charge particle moves through the RF cavity, the charge particle will loss energy and induce an field voltage $\boldsymbol{v}_q$, which oscillates with the cavity resonance frequency and decays exponentially with time constant $t_d=2Q_L/\omega_c$:

$$\boldsymbol{v}_q(t)=-q\cdot\omega_c\cdot\frac{R_s}{Q_0}\cdot\exp(j\omega_c t-\frac{t}{t_d}) \tag{9}$$

where t is the elapsed time since the field voltage is excited. With the superposition property of field voltage, we can write the beam-induced field voltage as

$$\boldsymbol{v}_b(t_0)=\sum_{m=-\infty}^{0}\boldsymbol{v}_q(t_0-t_m) \tag{10}$$

where t_m is the passed time of the charge particles through the cavity. As the usual process in digital RF feedback system, the RF signal is described by I-Q components:

$$v(\omega,t)=\Re[(I_v+jQ_v)\cdot\exp(j\omega t)] \tag{11}$$

Here we choose time reference such that $\exp(j\omega t_s)=1$, where t_s is arrival time of a synchronous charge particle at the RF cavity. The steady state I-Q components of the cavity voltage in Fig. 1 are then equal to

$$I_v=|v_c|\cdot\cos(\phi_s),\ Q_v=|v_c|\sin(\phi_s) \tag{12}$$

While the errors of the cavity voltage, δI_v and δQ_v, are detected as a charge particle passes through the cavity, an angle rotation θ_r is applied to the I-Q errors:

$$\begin{pmatrix}\delta I_v'(n)\\ \delta Q_v'(n)\end{pmatrix}=\begin{pmatrix}\cos(\theta_r) & -\sin(\theta_r)\\ \sin(\theta_r) & \cos(\theta_r)\end{pmatrix}\begin{pmatrix}\delta I_v(n)\\ \delta Q_v(n)\end{pmatrix} \tag{13}$$

where n represents the revolution number of a beam bunch. In the simulation the feedback I-Q components of $\boldsymbol{i}_g$ are given by

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$$I_g(n)=\delta I_v'(n)\cdot\frac{1+\beta}{R_s}\cdot k_p+I_{ig}$$
$$Q_g(n)=\delta Q_v'(n)\cdot\frac{1+\beta}{R_s}\cdot k_p+Q_{ig} \tag{14}$$

where k_p represents the feedback gain, I_{ig} and Q_{ig} are the desired value. If we consider time delay, we should use I_g(n-j) and Q_g(n-j), instead of I_g(n) and Q_g(n), in the calculation for $\boldsymbol{v}_g$. The longitudinal motion of a charge particle can be described by the two parameters, time and energy deviations, τ and ε, from the synchronous particle. The time development for ε and τ in the turn-by-turn motion can be described by [4]:

$$\varepsilon_{n+1}=\varepsilon_n+q[V_c(t_s+\tau_n)-U_{rad}(\varepsilon_n)]$$
$$\tau_{n+1}=\tau_n+\alpha\cdot T_0\cdot\frac{\varepsilon_{n+1}}{E_s} \tag{15}$$

where T_0 is the revolution period of the synchronous particle, $U_{rad}(\varepsilon)$ is the radiation loss during a revolution. If ε is converged in the longitudinal motion, we will judge that the beam current can be stored.

SIMULATION RESULT OF AN EXAMPLE CASE

With the formulae presented in the previous sections, the effect of this approach on beam loading was investigated by checking the threshold of the allowed stored beam current of an example case for different rotation angle θ_r. The machine parameters of the example case are listed in Table 1. The initial time deviation τ is set to zero, initial energy deviation ε is set to -300000 eV.

Table 1: Machine Parameters of the Example Case

Beam energy (GeV)	3.0
RF frequency (MHz)	499.65
Total RF voltage (kV)	2800
Radiation loss/turn (keV)	1200
Cavity number	2
Momentum compaction factor	2.3997×10^{-4}
Harmonic number	854
Q0	1.0×10^{9}
Qext = Q0/β	6.5×10^{4}
Rs/Q0	47.5
Bunch number	1

The result is shown in Fig. 2, in which φ is the rotation angle with reference to the cavity tuning angle ψ, given by Eq. (8), and the allowed stored beam current is normalized with the Robinson stability limit:

$$I_R=2\cdot\frac{V_c}{R_s}\cdot(1+\beta)\cdot\frac{\sin(\phi_s)}{\sin(2\phi_s)} \tag{16}$$

Figure 2 shows that the maximal stored beam current is, as prediction, affected by the rotation angle θr, and the maximal threshold of the stored beam current is occurred around φ = -25 degrees, deviated from the cavity tuning angle, for different feedback gain. It seems that the tuning angle ψ is a good reference for setting the rotation angle to alleviate the beam loading influence, which we judge by the allowed stored beam current.

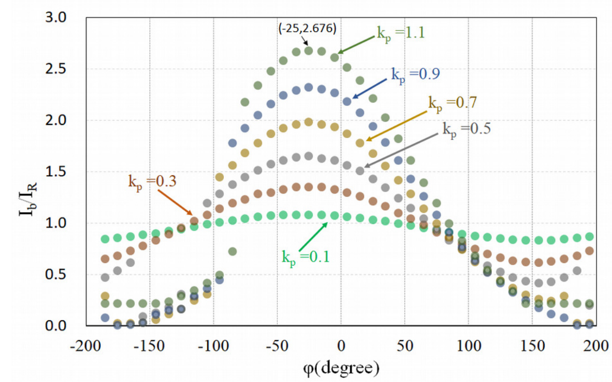

Figure 2: the maximal stored beam current versus the rotation angle at different feedback gain. The rotation angle θ_r in Eq.(13), is equal to φ-ψ. The machine parameters are listed on Table 1. The time delay for the example case is two revolution periods.

CONCLUSION

Beginning with examining how to match a beam-loaded RF cavity with the transmission line, the working mechanism for the presented approach was discussed. While loaded with beam current, the cavity frequency is detuned, that causes a phase difference between the feedback error $\delta\boldsymbol{v}_c$ and the correction $\delta\boldsymbol{v}_g$. This approach provides a way to change this phase difference in the existed RF feedback system. The numerical simulation has proved that it is able to reduce the beam loading effect on machine operation, which is judged by the maximum stored beam current. In the example case, the optimized rotation angle θ_r always occurs around -25 degrees away from the cavity tuning angle for different feedback gain. It seems that the cavity tuning angle is a good reference for setting the optimal rotation angle.

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