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Enhanced decoupling of MRI RF coil pairs during tuning of MRI RF transmit coil.

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This invention is generally directed to the art of magnetic resonance imaging (MRI) utilizing nuclear magnetic resonance (NMR) phenomena. It is more particularly directed to method and apparatus for enhancing proper detuning of an MRI RF receive coil during set-up tuning of a resonant MRI RF transmit coil.

In commercially available MRI systems, it is conventional practice to provide electrically controllable RF tuning/coupling capacitances associated with RF receive coils. Typically, such electrically controlled capacitances are realized as reverse biased varactor diodes. Such varactor diodes typically exhibit a capacitance versus voltage curve which provides for increasing capacitance as the reverse voltage across the diode is reduced in magnitude or, conversely, reduced capacitance as the reverse bias voltage across the diodes is increased in magnitude.

Since commercial MRI systems employ sophisticated computer control capabilities, it is quite understandable that they already provide for automatic computer-controlled tuning of these receiver coils by suitably controlling the reverse bias voltage across such varactor diodes. Since the resonant frequency and Q of the transmit/receive coils is affected by the individual properties of a patient's tissue which is coupled to such coils during MRI procedures, there is typically an initial "setup" procedure performed after the coils are in place with respect to a particular patient's anatomy within the MRI magnet, etc. During this initial setup phase, preparatory to actual imaging sequences, an operator typically tunes the transmit coil variable capacitors for a desired resonance and for maximum coupling (i.e., a matched impedance condition with the RF transmission line and transmitter).

For various reasons well-known in the art, if a separate RF receive coil is being utilized, it is desirable to have that coil decoupled from the transmit coil during such setup tuning procedures. For example, it has heretofore been customary for the reverse bias voltage supplied to receive coil varactors to be reduced to minimum magnitude (i.e., zero volts) during setup tuning of the transmit coil. By this technique, the effective capacitance of such varactor diodes is (hopefully) considerably increased thus, in effect, detuning and decoupling the receive coil from the transmit coil as the latter is being tuned.

However, if the tuned receiver coil already uses a reverse bias voltage near zero volts, then the detuning effect may not be achieved to the degree desirable. This possible lack of desired detuning effect would become even more pronounced if plural varactors are connected in parallel (i.e., to obtain greater tuning range) since lower tuned coil varactor voltage magnitudes may typically be expected.

Using such prior automatic detuning techniques, it has typically been possible to detune the receiver coil by a maximum of approximately 2 MHz (e.g., from a resonant frequency of about 15 MHz to a lower off-resonant frequency of about 13 MHz). While this has provided some significant decoupling of the receive coil during transmit coil tuning, additional decoupling is still desirable. And it would be advantageous to permit use of plural parallel-connected varactor diodes.

We have now discovered that such objects can be achieved by the simple expedient of applying a suitable forward bias voltage to the varactor diodes of the receive coil during transmit coil tuning procedures. In other words, the normal polarity of the varactor diode bias voltage (i.e., so as to reverse bias the diode) is reversed (i.e., so as to forward bias the diode) to achieve enhanced decoupling and detuning of the receive coil. It has also been discovered that the desirable decoupling and detuning effect increases with an increasing magnitude of forward bias voltage to the varactor diode.

It has also been discovered that use of parallel-connected varactor capacitances (so as to achieve greater total tunable capacitance) is now facilitated by such new detuning procedures.

These as well as other objects and advantages of this invention will be more completely appreciated by carefully studying the following detailed description of a presently preferred exemplary embodiment of this invention when taken in conjunction with the accompanying drawings, of which:

FIGURE 1 is a schematic diagram of an MRI system modified so as to practice this invention;
FIGURE 2A is a detailed schematic diagram of the receive coil with a typical prior art arrangement of varactor diodes with computer controlled switched bias voltage source using grounded leads for detuning;
FIGURE 2B is a detailed schematic diagram of a receive coil with parallel-connected varactor diodes and a switched polarity detuning bias source in accordance with a presently preferred exemplary embodiment of this invention;
FIGURE 3 is a schematic graphical depiction of the manner in which capacitance and associated RF losses in a typical varactor diodes device vary as a function of applied bias voltage;
FIGURE 4 depicts a graph of relative coupling between transmit/receive coil pairs for different varactor diodes bias voltages; and
FIGURE 5 is a graphical depiction of the resonant response of the detuned receive coil for selected different varactor diode forward bias voltages.

FIGURE 1 schematically depicts some of the elements of a typical MRI system. For example, a patient 10 is typically coupled to a transmit coil 12 and to a receive coil 14. Both coils may be tuned to suitable resonant frequencies by associated parallel capacitances $C_p$ and suitably adjusted via series capacitance(s) $C_s$ to an RF transmitter 16 and RF receiver 18 associated with an MRI RF section 20 which is, in turn, typically controlled by an MRI control and processing unit 22. During MRI imaging sequences, the control unit 22 causes a programmed sequence of RF pulses to be transmitted via transmit coil 12 into the tissue of patient 10 while suitable gradients are produced in a static magnetic field $H_0$ via suitable magnetic gradient coils (not shown). NMR RF responses are received via receive coil 14 and processed so as to produce an image at monitor 24 (and/or to store image data, etc.). The whole system is typically controlled from a suitable operator console 26.

As previously explained, commercially available MRI systems already typically realize the RF receiver coil series capacitances and/or parallel tuning capacitances (at least in part) as varactor diodes which are appropriately reverse biased. Such bias control is typically provided via line(s) 30 during automatic or manual tuning for impedance match and resonance during conventional MRI setup procedures. As previously explained, it is also conventional for the control unit 22 to simultaneously detune varactor diodes associated with the separate receive coil, if any (e.g., during the tuning of the transmit coil), via suitable changes in the varactor diode bias voltages supplied via line(s) 30. In the past, such detuning bias voltages on lines 30 have been in the form of reducing the reverse bias voltage magnitude to a minimum value (thus, hopefully, substantially increasing the capacitance and lowering the resonant frequency of the receive coil 14).

However, as depicted in FIGURE 1, in accordance with this invention, the detuning control via line(s) 30 to the receive coil varactor diodes actually reverses polarity so as to forward bias such varactor diodes and thus to provide and enhance the degree of automatic detuning during transmit coil tuning procedures.

Since existing commercially available MRI systems typically already provide for automatic de-tuning of the receive coil while tuning the transmit coil (e.g., by concurrently automatically changing the bias voltage supplied to varactor diodes associated with the receive coil), it is not believed necessary to burden the present discussion with a detailed description of how such automatic controls are programmed within the control algorithm of the control unit 22. Rather, all that is necessary is that such existing control algorithms be slightly modified so as to reverse the polarity of the detuning bias voltage supplied via line(s) 30 -- and to control it to a suitable magnitude.

A typical prior art MRI RF receive coil circuit is depicted in FIGURE 2A. The varactor diodes $D_1$ through $D_7$ are arranged to provide coupling/matching capacitances $C_p$ and at least part of the parallel tuning capacitance $C_s$. Resistances $R$ isolate the dc varactor bias circuit from the RF circuit. Switch S1 normally connects the diodes $D_1$ - $D_7$ with a source of reverse bias from battery 60 which is adjustable via potentiometers 62 and 64 to provide independent adjustment of $C_p$ and $C_s$ capacitances. Upon receiving a detune command from the control computer, relay K1 actuates switch S1 contacts so as to ground the bias control leads of the varactors $D_1$ - $D_7$; thus reducing the reverse bias to a minimum zero value (or to some other relatively smaller magnitude of reverse bias voltage).

Although those in the art will no doubt appreciate that reverse polarity and magnitude control in accordance with this invention can be achieved in many different ways, one possible scheme is schematically depicted at FIGURE 2B. As can be seen in FIGURE 2B, varactor diodes $D_1$ through $D_7$ are arranged to provide the coupling/matching capacitances $C_p$ and (at least part of the) parallel tuning capacitance $C_s$ associated with receive coil 14. Suitable DC bias control circuits are again isolated from RF via strategically positioned resistances $R$. Relay K1 and contacts of switch S1 normally connect the varactors with reverse bias voltage adjustable in magnitude via potentiometers 62 and 64 (with a minimum tuned bias of about 3. volts being defined by resistances 62 and 64). Now, however, when a detune command from the control computer actuates relay coil K1, the contacts of switch S1 provide a forward bias of 24 volts across the varactors via battery 70.

In FIGURE 2B, such forward bias voltage is supplied at a fixed level. However, as those in the art will appreciate, suitable additional controllable attenuators may be provided in association with the reverse polarity bias voltage so as to also provide a controllable magnitude of forward bias to the varactor diodes during receiver coil detuning times.

As can be seen in FIGURE 2B, each varactor $D_1$ - $D_7$ has an additional pair of similar varactors $D^*$, $D^*$ connected in parallel therewith. This provides a greater range of tunable capacitance over a smaller range of bias voltage. It also permits use of a smaller fixed capacitance $C_{ps}$ in the parallel tuning capacitance.

As depicted in FIGURE 3, the capacitance of a varactor diode typically decreases as the magnitude of reverse bias is increased. Typical ranges of operating reverse bias for the varactor voltages (for both the old and new arrangements) are depicted in FIGURE 3. As depicted in FIGURE 3, is a typical prior art minimum detuning bias voltage (e.g., 0 volts) overlapped somewhat with the possible tuning range of bias voltages. Also
depicted in FIGURE 3 lines is a schematic depiction of typical RF losses that may be associated with varactor diodes. As shown, such RF losses remain at fairly low levels so long as the diode is reverse biased (as it is during normal conventional operation).

However, in accordance with this invention, it is now proposed that, during detuning times, the polarity of the varactor diode bias voltage be reversed (e.g., so as to forward bias the diodes) to significant values (e.g., -5 volts, -10 volts, -40 volts, etc). As may be generally observed from the schematic depiction of FIGURE 3, the capacitance of the varactor continues to increase and, in addition, the RF losses associated with the capacitance will dramatically increase as the varactor diodes become forward biased to an ever greater extent.

A graphical depiction of coupling between the transmit and receive coils resulting from four different varactor diode bias voltages is depicted at FIGURE 4. As can be seen, at a center frequency of 14.5 MHz (e.g., the center resonant frequency of the transmit coil), a zero varactor diode bias voltage produced approximately -15 dB of isolation between the coils. However, when the varactor diodes are forward biased (e.g., by a negative voltage with respect to ground in the circuit of FIGURE 2), the magnitude of decoupling increases. For example, at -5 volts, the coupling between coils decreases to -20 dB. At -24 volts, the coil coupling decreases even further to approximately -28 dB. And at a forward bias magnitude of 40 volts, the decoupling increases still further to approximately -36 dB. All of these degrees of decoupling are substantially greater (and therefore more desirable) than that which was attainable using prior conventional detuning techniques.

Such enhanced decoupling is accompanied by an enhanced detuning of the resonant frequency of the receive coil away from the resonant frequency of the transmit coil. For example, the resonant response of the detuned receive coil is depicted in FIGURE 5 for three different varactor diode bias voltage magnitudes. As can be seen, for a zero varactor diode bias voltage, the resonant response of the receive coil is detuned from the nominal center frequency (e.g., 15 MHz) by approximately 2.1 MHz (e.g., not that much different from what is achievable with conventional practices). However, when the varactor diodes are forward biased by a magnitude of 5 volts, the resonant response of the receiver coil is shifted from the center frequency by approximately 4.8 MHz. At a varactor diode bias of -10 volts, the resonant response is shifted still further to approximately 5.4 MHz from the center frequency.

As should now be appreciated, the simple expedient of reversing the polarity (and suitably controlling the magnitude) of the varactor diode bias voltage supplied to the receive coil during transmit coil tuning procedures provides for materially enhanced detuning and decoupling of the receive coil from the transmit coil. And, by limiting the normal tuning bias voltage range (e.g., from 3 to 25 volts rather than from 0 to 25 volts), an enhanced detuning effect is also achieved.

The following table compares the prior art approach to detuning with that of this invention.

<table>
<thead>
<tr>
<th>Tuning Receiving</th>
<th>( V_{\text{parallel}} )</th>
<th>( V_{\text{series}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>RF Coil (old)</td>
<td>0 to +25V</td>
<td>0 to +25V</td>
</tr>
<tr>
<td>Detuning (old)</td>
<td>0 volts</td>
<td>0 volts</td>
</tr>
<tr>
<td></td>
<td>(fixed)</td>
<td>(fixed)</td>
</tr>
<tr>
<td>Tuning Receiving</td>
<td>(+3) to +25V</td>
<td>(+3) to +25V</td>
</tr>
<tr>
<td>RF Coil (New)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Detuning (New)</td>
<td>-24V</td>
<td>-24V</td>
</tr>
<tr>
<td></td>
<td>(fixed)</td>
<td>(fixed)</td>
</tr>
</tbody>
</table>
It is quite apparent that if prior art tuning (not detuning) voltage for receiver coils happened to be near zero volts (as often happened), one would not get much, if any detuning effect.

While only one exemplary embodiment of this invention has been described in detail, those skilled in the art will recognize that many variations and modifications may be made in this exemplary embodiment while yet retaining many of the novel features and advantages of this invention. Accordingly, all such modifications and variations are intended to be included within the scope of the appended claims.

Claims

1. An MRI system comprising:
an RF transmit coil (12) and an RF receive coil (14) including at least one varactor diode element (D1, D2, D3, D4, D6, D7) providing an RF tuning and/or matching capacitance as a function of reverse bias voltage thereacross during active RF receive times and for detuning said RF receive coil (14) to decouple it from said RF transmit coil (12) at selected other times, and

means (K1) for reversing the polarity of bias voltage across said varactor diode element (D1, D2, D3, D4, D6, D7) so as to forward-bias it to detune the RF receive coil (14).

2. An MRI system according to claim 1, characterized in that
said RF transmit coil (12) includes parallel capacitances (Cp) and series capacitance(s) (Cs) for changing its resonant frequency and transfer coupling impedance; and

including control means (22) for tuning said series capacitance(s) (Cs) of said RF transmit coil (12) to a resonant and matched impedance state in which said transmit coil (12) resonates and accepts transfer of maximum RF power at a predetermined RF frequency;
said control means (22) including means (K1) for detuning said RF receive coil (14) to a low off-resonance state during said tuning of said RF transmit coil (12) by applying a forward bias voltage across said varactor diode element (D1, D2, D3, D4, D6, D7).

3. An MRI system according to claim 2, characterized in that
said RF receive coil includes an inductance (14);
a parallel tuning capacitance (Cp) including a plurality of parallel-connected varactor diodes (D1, D2) with a tuning bias voltage (60) connection thereacross; and

a pair of balanced series capacitances (Cs) each including a plurality of parallel-connected varactor diodes (D3, D4, D6, D7) with a tuning bias voltage (60) connection thereacross; and

said control means (22) includes means (70) for reversing the polarity of voltage applied to tuning bias voltage connections of said RF receive coil (14).

4. An MRI method comprising:
operation of an RF transmit coil (12) and operation of an RF receive coil (14) so as to decouple said receive coil (14) from said transmit coil (12) during tuning of said transmit coil (12) and including at least one varactor diode element (D1) in circuit with said receive coil (14) to tune its resonant frequency by controlling the reverse bias of said varactor diode element (D1), and

using said varactor diode element (D1) both for tuning said receive coil by reverse biasing it and for detuning it by forward biasing it.

5. A method according to claim 4, wherein said receive coil (14) is connected in parallel tuned circuit with
at least one pair of parallel-connected varactor diodes (D1, D1’, D1”, D2, D2’, D2”) and also connected with an RF coupling circuit including at least one further pair of parallel-connected varactor diode (D3, D3’, D3”, D4, D4’, D4”), said varactor diodes providing predetermined capacitance when reverse biased with a predetermined voltage, said using step comprising the application of forward bias voltage to said plurality of varactor diode elements so as to greatly increase the capacitance and resistive losses thereof.

Patentansprüche

1. System zur Bilderkennung mittels magnetischer Resonanz mit:
einer HF-Sendespule (12) und einer HF-Empfangsspule (14) mit zumindest einem Varaktordiodenelement (D1, D2, D3, D4, D6, D7), das eine HF-Abstimmungs- und/oder Anpassungs-Kapazität als Funk-
tion der daran anliegenden Sperr-Vorspannung während aktiver HF-Empfangszeiten bereitgestellt, und zum Verstimmern der HF-Empfangsspule (14), um sie zu ausgewählten anderen Zeiten von der HF-Sendespule (12) zu entkoppeln, und einer Vorrichtung (K1) zum Umkehren der Polarität der Vorspannung am Varaktordiodenelement (D1, D2, D3, D4, D6, D7), um es zur Verstimmung der HF-Empfangsspule (14) in Durchläßrichtung vorzuspannen.

2. System zur Bildерzeugung mittels magnetischer Resonanz nach Anspruch 1, dadurch gekennzeichnet, daß die HF-Sendespule (12) parallele Kapazitäten (Cp) und serielle Kapazität(en) (Cs) enthält, um seine Resonanzfrequenz und Sendekoppelimpedanz zu verändern; und eine Steuervorrichtung (22) enthalten ist, um die serielle(n) Kapazität(en) (Cs) der HF-Sendespule (12) auf einen Resonanz- und angepaßten Impedanz-Zustand abzustimmen, in welchem die Sendespule (12) resoniert und bei einer vorgestimmten Hochfrequenz ein Senden mit maximaler HF-Energie gestattet, wobei die Steuervorrichtung (22) eine Vorrichtung (K1) zum Verstimmern der HF-Empfangsspule (14) auf niedrigen Nichtresonanz-Zustand während des Abstimmens der HF-Sendespule (12) durch Anlegen einer Durchläß-Vorspannung an das Varaktordiodenelement (D1, D2, D3, D4, D6, D7) enthält.

3. System zur Bildzeugeung mittels magnetischer Resonanz nach Anspruch 2, dadurch gekennzeichnet, daß die HF-Empfangsspule eine Induktivität (14) enthält; eine parallele Abstimmungs-Kapazität (Cp) eine Vielzahl von parallel verbundenen Varaktordioden (D1, D2) mit einer Abstimmungsvorspannungs(60)-Verbindung daran enthält; und ein Paar von ausbalancierten seriellen Kapazitäten (Cs) jeweils eine Vielzahl von parallel verbundenen Varaktordioden (D3, D4, D6, D7) mit einer Abstimmungsvorspannungs(60)-Verbindung daran enthält; und die Steuervorrichtung (22) eine Vorrichtung (70) zum Umkehren der Polarität der an die Abstimmungsvorspannungs-Verbindungen der HF-Empfangsspule (14) angelegten Spannung enthält.

4. Verfahren zur Bildzeugeung mittels magnetischer Resonanz umfassend: Betreiben einer HF-Sendespule (12) und Betreiben einer HF-Empfangsspule (14) derart, um die Empfangsspule (14) von der Sendespule (12) während der Abstimmung der Sendespule (12) zu entkoppeln und Vorehren zumindest eines Varaktordiodenelements (D1) im Kreis mit der Empfangsspule (14), um dessen Resonanzfrequenz durch Steuern der Sperr-Vorspannung des Varaktordiodenelements (D1) abzustimmen, und Verwenden des Varaktordiodenelements (D1) sowohl zum Abstimm der Empfangsspule durch Anlegen einer Sperr-Vorspannung als auch zum Verstimm derselben durch Anlegen einer Durchläß-Vorspannung.

5. Verfahren nach Anspruch 4, wobei die Empfangsspule (14) in einem Parallelschwingkreis mit zumindest einem Paar parallel verbundenen Varaktordioden (D1, D1', D1", D2, D2', D2") verbunden ist und auch mit einer HF-Koppschaltung mit zumindest einem weiteren Paar parallel verbundenen Varaktordioden (D3, D3', D3", D4, D4', D4") verbunden ist, wobei die Varaktordioden eine vorgestimmte Kapazität aufweisen, wenn sie mit einer vorgestimmten Spannung in Sperrrichtung vorgespannt werden, wobei der Verwendungsschritt das Anlegen einer Durchläß-Vorspannung an die Vielzahl von Varaktordiodenelementen umfaßt, um deren Kapazität und ohmsche Verluste stark zu erhöhen.

Reveniations

1. Un système d'imagerie par résonance magnétique comprenant :
   une bobine de transmission haute-fréquence (12) et une bobine de réception haute-fréquence (14), comprenant au moins un élément à diode à capacité variable (D1, D2, D3, D4, D6, D7), fournissant un accord haute-fréquence et/ou une capacité d'adaptation en fonction d'une tension de polarisation inverse la traversant pendant des périodes de réception HF actives et pour désaccorder ladite bobine de réception haute-fréquence (14) afin de la découpler vis-à-vis de ladite bobine de transmission HF (12) pendant d'autres périodes de temps sélectionnées et,
des moyens (K1) pour inverser la polarité de la tension de polarisation passant dans ledit élément à diode à capacité variable (D1, D2, D3, D4, D6, D7), de façon à lui donner une polarisation directe entraînant le désaccord de la bobine de réception HF (14).

2. Un système d'imagerie à résonance magnétique selon la revendication 1, caractérisé en ce que ladite bobine de transmission HF (12) comprend des condensateurs parallèles (Cp) et des condensateurs série (Cs) pour modifier sa fréquence de résonance et son impédance de couplage de transfert; et comprenant des moyens de commande (22) pour accorder lesdits condensateurs série (Cs) de ladite bobine de transmission HF (12) à un état de résonance et d'adaptation d'impédance dans lequel ladite bobine de transmission (12) entre en résonance et accepte un transfert d'une puissance HF maximale à une fréquence HF prédéterminée; ledit moyen de commande (22) comprenant un moyen (K1) pour désaccorder ladite bobine de réception HF (14) à un état bas, hors de résonance, pendant ledit accord de ladite bobine de transmission HF (12), par application d'une tension de polarisation directe sur ledit élément à diode à capacité variable (D1, D2, D3, D4, D6, D7).

3. Un système d'imagerie à résonance magnétique selon la revendication 2, caractérisé en ce que ladite bobine de réception HF comprend une inductance (14); un condensateur d'accord parallèle (Cp) comprenant une pluralité de diodes à capacité variable (D1, D2) reliées en parallèle avec une liaison de tension de polarisation d'accord (60); et un couple de condensateurs série (Cs) équilibrés comprenant chacun une pluralité de diodes à capacité variable (D3, D4, D6, D7) reliées en parallèle avec une liaison de tension de polarisation d'accord (60); et ledit moyen de commande (22) comprenant un moyen (70) pour inverser la polarité de la tension appliquée aux liaisons de tension de polarisation d'accord de ladite bobine de réception HF (14).

4. Procédé d'imagerie à résonance magnétique comprenant : le fonctionnement d'une bobine de transmission HF (12) et le fonctionnement d'une bobine de réception HF (14) de façon à découpler ladite bobine de réception (14) de ladite bobine de transmission (12) pendant l'accord de ladite bobine de transmission (12) et comprenant au moins un élément à diode à capacité variable (D1) mis en circuit avec ladite bobine de réception (14) pour accorder sa fréquence de résonance par commande de la polarisation inverse dudit élément à diode à capacité variable (D1) et utilisation dudit élément à diode à capacité variable (D1) à la fois pour accorder ladite bobine de réception par application d'une polarisation inverse et pour le désaccorder en lui appliquant une tension de polarisation directe.

5. Procédé selon la revendication 4, dans lequel ladite bobine de réception (14) est reliée dans un circuit d'accord en parallèle, avec au moins un couple de diodes à capacité variable (D1, D1', D1", D2, D2', D2") branchées en parallèle et reliées également à un circuit de couplage HF comprenant au moins un couplé supplémentaire de diodes à capacité variable (D3, D3', D3", D4, D4', D4") reliées en parallèle, lesdites diodes à capacité variable donnant des capacités prédéterminées une fois l'objet d'une polarisation inverse avec une tension prédéterminée, ladite étape d'utilisation comprenant l'application de tension de polarisation directe sur ladite pluralité d'éléments à diodes à capacité variable de façon à augmenter fortement leur capacité et leurs pertes résistives.
COUPLING BETWEEN RF COIL PAIRS

![Graph showing coupling between RF coil pairs with dB values and frequency range](image)

\[ f_0 = 14.5 \text{ MHz} \]