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Introduction of a Pseudo-6th Order ISDN Splitter with Bandstop Topology

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***Abstract*—A newly developed 'integrated services digital network' (ISDN) splitter with bandstop (BS) topology is presented and compared to an actual ISDN splitter with a traditional low-pass (LP) topology. The LP-to-BS topology change reduced the amount of filter stages: a LP ISDN splitter requires an 8th order elliptic-like filter in order to be compliant to the standard 'TS 101 952-1-4 V1.1.1' [1] of the European Telecommunications Standards Institute (ETSI), whereas the BS ISDN splitter only needs a pseudo-6th order elliptic-like filter. The design of the new BS ISDN filter is discussed in the light of the enforced ETSI specifications. Furthermore, both the ISDN splitters are compared in the field of their specific stopband performance and their physical implementation. The area reduction that comes together with the introduction of the new ISDN splitter with BS topology is more than 25%.**

I. Introduction

The ADSL-ISDN/POTS splitter is a frequency-selective three-port that is utilized for central office (CO) deployment in an ADSL over 'ISDN or POTS' system and that separates the transmission of either baseband POTS ('plain old telephone service') or ISDN signals and broadband ADSL ('asymmetric digital subscriber line') signals, enabling the simultaneous transmission of the two services on the same line (=twisted pair). In other words, the ADSL-ISDN/POTS splitter serves either as an ADSL-POTS splitter or as an ADSL-ISDN splitter depending on the POTS or ISDN signals at the '+isdn' and '-isdn' terminals, respectively. However, as the ISDN service can be offered in two different line modes, namely 2B1Q and 4B3T, the ADSL-ISDN/POTS splitter turns out to be a three-in-one splitter combination: an ADSL-POTS splitter, or an ADSL-ISDN 2B1Q splitter or an ADSL-ISDN 4B3T splitter.

The block scheme of such an ADSL-ISDN/POTS splitter is shown in fig. 1 and comprises a low pass (LP) and high pass (HP) filter. The splitter is connected to the telephone exchange or ISDN transceiver by means of the '+isdn' and '-isdn' terminals and is attached to the line through the '+line' and '-line' nodes. The '+adsl' and '-adsl' terminals of the splitter lead to the ADSL transceiver.

The main filter function of the LP section of the ADSL-ISDN/POTS splitter, hereafter abbreviated as the ISDN splitter, consists of the bidirectional interference suppression between the ADSL signals (from 138kHz to 2.2MHz) on the one hand and the ISDN (from 1kHz to 80kHz) or telephone service (POTS signals, from 300Hz to 4kHz) on the other hand.

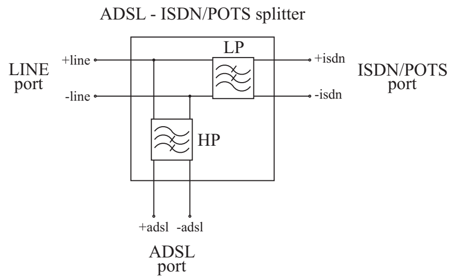

Fig. 1: Architecture of the ADSL-ISDN/POTS splitter

Two major drawbacks of passive ISDN splitters are the need for higher order filters and the need for large transformers. The fact that multiple stages are required in ISDN splitters is directly coupled to the instructed large stopband attenuation that must be achieved in a small pass- to stopband window. The necessity for large transformers, on the other hand, originates from the relatively low cut-off frequency and the compelled high transformer saturation levels.

A classical technique for reducing the splitter's size, is the replacement of the transformers [2]–[5] or entire filter sections [6]–[9] by an active equivalent. These active splitter solutions do satisfy their size optimizing goal, but also introduce several weaknesses: first, an evident and continous power consumption, second, a reduced large signals endurance and last but not least, a heavily disturbed ADSL service if the active filter part fails (except for [8] and [9]). These drawbacks associated with the active splitter versions push strongly towards a passive revival, whenever possible. In this paper, a newly developed fully passive ISDN splitter with a BS topology is presented and compared to an actual ISDN splitter with a traditional LP topology. Both these splitters are discussed and compared in the field of high-frequency performance and overall size.

II. Terminology and Specifications

The ISDN splitter is expected to be adequate under a wide range of electrical operational conditions in order to fulfil the

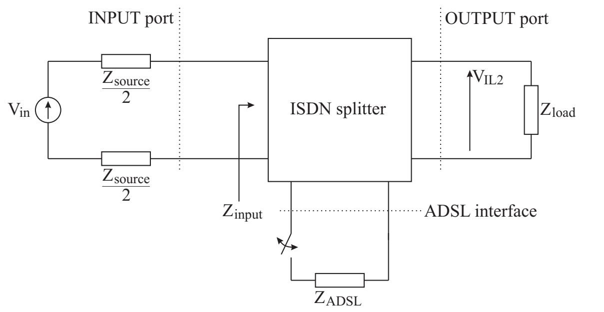

Fig. 2: General splitter set-up for IL and RL visualisation

splitter mode	ADSL switch	$Z_{\mathtt{source}}$	$Z_{\mathtt{load}}$	freq. range (in kHz)	IL spec. (in dB)
POTS	open/closed	Z_R	Z_R	1	$<$ 1
	closed	Z_{RHF}	100Ω	32-2208	$>$ 55
ISDN (2B1Q)	closed	135Ω	135Ω	1-40	$<$ 0.8
				40-80	$<$ 2.0
	open	135Ω	135Ω	1-40	$<$ 1.0
				40-80	$<$ 2.5
	closed	135Ω	100Ω	138-150	$>$ 55
				150-1104	$>$ 65
				1104-2208	$>$ 55

TABLE I: Overview of the IL-related ISDN splitter specifications according to the ETSI-standard 'TS 101 952-1-4 V1.1.1'

ETSI standard 'TS 101 952-1-4 V1.1.1'. All these conditions are related to one basic splitter set-up that is presented in fig. 2. Due to the required bidirectionality of the splitter's filter function, the INPUT port in fig. 2 is alternately set to the LINE and ISDN/POTS port of the ISDN splitter, while the OUTPUT port is fixed on the ISDN/POTS and LINE port, respectively. Note that the switch in fig. 2 effects an open or terminated ADSL interface.

The qualification of the splitter's electrical performance in the set-up is measured through some figures of merit. The most predominant figure of merit is the insertion loss (IL). By definition the IL of an electronic filter is the measure for the decrease in transmitted power into a load, resulting from the insertion of this filter. In relation to the ISDN splitter set-up (fig. 2), the IL definition (in dB) can be expressed as:

$$\mathrm{IL}(f) = -20 \cdot \log_{10} \frac{V_{\mathtt{IL2}}(f)}{V_{\mathtt{IL1}}(f)} \tag{1}$$

in which $V_{\mathtt{IL2}}$ and $V_{\mathtt{IL1}}$ are the voltages over the load impedance $Z_{\mathtt{load}}$ with and without the splitter inserted, respectively.

The most important IL-related test conditions of the ETSI standard 'TS 101 952-1-4 V1.1.1', together with the demanded levels of IL, are summarized in table I. The specifications of the ISDN 4B3T mode are not presented as they are similar to the specifications of the ISDN 2B1Q mode. The detailed description of the load impedances Z_R and Z_{RHF}, mentioned in table I, can be found in [1].

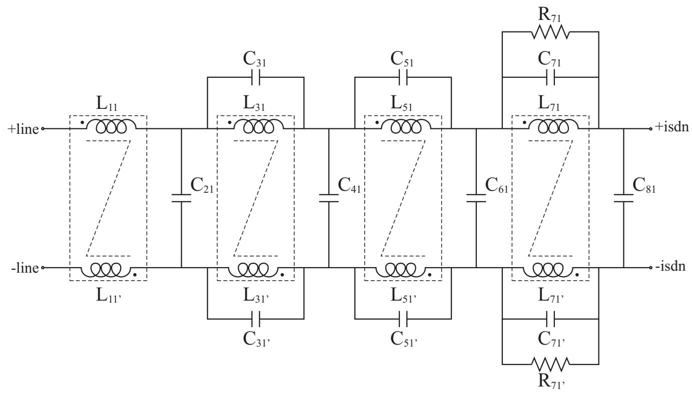

Fig. 3: The circuit topology of the actual 8th order LP ISDN splitter

III. ISDN SPLITTER WITH LP TOPOLOGY

The circuit topology of an actual 8th order ETSI compatible LP ISDN splitter for complex impedances is shown in fig. 3 and compromises four stages: an LC filter cel, two undamped elliptic cells and, finally, a damped elliptic cell. This schematic is a balanced implementation and, hence, the values of corresponding network elements in each of the branches are equal.

The actual ISDN splitter is an 8th order standard elliptic LP filter that is altered in order to fulfil all ISDN specifications: the elliptic capacitors over the inductors L_{11}-$L_{11'}$ are withdrawn and some damping resistors are added onto the last elliptic stage. One of the consequences of dropping the capacitors over the inductors L_{11}-$L_{11'}$ is the loss of two transmission zeros in the stopband. This means that the actual LP ISDN filter only implements six zeros at the following frequencies:

$$\begin{aligned} f_{\mathtt{z11}} = f_{\mathtt{z21}} &= \frac{1}{2\pi \cdot \sqrt{2L_{31}C_{31}}} \\ f_{\mathtt{z31}} = f_{\mathtt{z41}} &= \frac{1}{2\pi \cdot \sqrt{2L_{51}C_{51}}} \\ f_{\mathtt{z51}} = f_{\mathtt{z61}} &\cong \frac{1}{2\pi \cdot \sqrt{2L_{71}C_{71}}} \end{aligned} \tag{2}$$

On the other hand, removing these elliptic capacitors increases the high-frequency attenuation from 20dB/decade to 40dB/decade.

IV. ISDN SPLITTER WITH BS TOPOLOGY

The idea for the introduction of an new splitter topology is the fact that there are relaxed stopband specifications and even no stopband specifications imposed for frequencies above 1.1MHz and above 2.2MHz, respectively (cf. table I). This implies that a pure LP filter with a stopband range from 138kHz till ∞, as described in previous paragraph, exhibits some overkill in comparison to a BS circuit with a stopband range from f_L=138kHz till f_H=2.2MHz. The latter really matches the stopband specifications.

In the following, the general design procedure for standard BS filters is presented and applied to the ISDN splitter case.

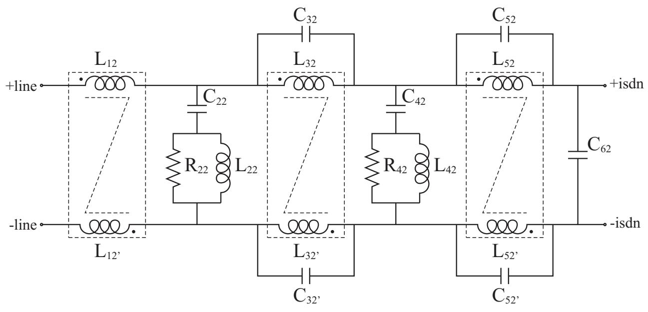

Fig. 4: The circuit topology of the novel pseudo-6$^{\text{th}}$ order BS ISDN splitter [10]

A. Standard BP filter design

The design flow of standard BS filters involves three major stages: the design of a suitable normalized LP filter, the transformation of the normalized LP filter into an appropriate HP filter and, finally, the transformation of this HP filter into a BS filter. In the following, each of these steps is explained in more detail.

1) Normalized LP filter: A normalized LP filter follows a predefined IL curve (Butterworth, Chebyshev, elliptic, ...) in-between 1Ω loads, with a passband that runs from 0 till 1Hz. The selection of the normalized LP filter is decided on the basis of three parameters: the minimum required steepness factor $A_{\mathtt{s}} = f_{\mathtt{stop}} \cdot (f_{\mathtt{pass}})^{-1}$, the tolerable IL ripple $R_{\mathtt{pass}}$ in the passband and the minimum IL attenuation $R_{\mathtt{stop}}$ in the stopband.

2) LP-to-HP transformation: The normalized LP filter is transformed into a normalized HP filter by simply interchanging every capacitor C_{LP} and inductor L_{LP} by an inductor L_{HP}=C_{LP}^{-1} and a capacitor C_{HP}=L_{LP}^{-1}, respectively. This normalized HP filter is then frequency scaled in order to fix the cut-off frequency f_{HP} of the issued HP filter to the final BS filter's bandwidth (f_{HP}=f_{H}-f_{L}). Finally, the new HP filter is also subjected to an impedance scaling in order to match the desired impedance level of the final BS filter.

3) HP-to-BS transformation: The BS filter is obtained when every element of the acquired HP filter is resonated to the BS bandwidth's centre frequency f_0=$\sqrt{f_{\text{L}} \cdot f_{\text{H}}}$. In practice, this transformation signifies that every capacitor C_{HP} in the HP filter is to be replaced by a parallel connection of a capacitor C_{BS}=C_{HP} with an inductor L_{BS}=$(\omega_0^2 C_{\text{HP}})^{-1}$ and that every inductor L_{HP} in the HP filter is to be replaced by a series connection of an inductor L_{BS}=L_{HP} with a capacitor C_{BS}=$(\omega_0^2 L_{\text{HP}})^{-1}$. Note that the final BS filter will be of the order $2n$ if the order to the initially chosen normalized LP filter equals n.

B. ISDN compliant BS filter

All filters that follow the ETSI standard show a minimum steepness factor of 1.725 (=138kHz·(80kHz)$^{-1}$) and minimum stopband attenuation of 65dB (cf. table I). If these characteristic values are combined with an passband ripple of e.g. 0.05dB, the minimum required order for a pure resistively terminated LP filter is calculated to be 10 or 7 in case of a Chebyshev or elliptic filter, respectively. As the final filter size plays a major role, it is not surprising that an elliptic LP filter topology is selected as the foundation for a final ISDN splitter. The starting order of the normalized LP, however, is set to 6. This is one order less than the above calculated 7 and two orders less than the LP ISDN splitter. The reason for this order reduction is the fact that the BS circuit manifests the double amount of transmission zeros in the stopband then its base LP counterpart. And, evidently, the more transmission zeros are available, the easier it gets to fulfil the stopband specifications.

Once all design stages are passed through, one acquires a 12$^{\text{th}}$ order (=2x6) standard elliptic BS filter that follows the prescribed IL curve for only one set of purely resistive terminations. The final ISDN splitter, however, has to comply to the same specifications but for multiple sets of load impedances that are, moreover, not all purely resistive. This implies that the given design sequence has to be repeated in an iterative way: the parameters steepness factor, IL ripple and IL attenuation are set more tight or loose according to the obtained results of the previous iteration.

After several design iterations, simulations and simplifications, the final 10$^{\text{th}}$ order ETSI compatible BS ISDN splitter for complex impedances is obtained. The circuit topology of the novel BS ISDN splitter, which only compromises three stages, is shown in fig. 4. It is clearly a stripped-to-the-bone standard elliptical BS filter in which only 8 of the original 12 transmission zeros of the standard BS filter are retained:

$$\begin{aligned} f_{z12} = f_{z22} &= \frac{1}{2\pi \cdot \sqrt{2\mathrm{L}_{32}\mathrm{C}_{32}}} \\ f_{z32} = f_{z42} &= \frac{1}{2\pi \cdot \sqrt{2\mathrm{L}_{52}\mathrm{C}_{52}}} \\ f_{z52} = f_{z62} &\cong \frac{1}{2\pi \cdot \sqrt{2\mathrm{L}_{22}\mathrm{C}_{22}}} \\ f_{z72} = f_{z82} &\cong \frac{1}{2\pi \cdot \sqrt{2\mathrm{L}_{42}\mathrm{C}_{42}}} \end{aligned} \qquad (3)$$

The resonance of the capacitor C_{62} in series with an inductor L_{62} would also issue two transmission zeros, but these zeros introduce no added value in obtaining the required stopband profile. Hence, no inductor L_{62} is incorporated in the final BS ISDN splitter circuit. Note that again two transmission zeros are lost due to the missing capacitors over the inductors L_{12}-$\mathrm{L}_{12'}$.

The new BS ISDN splitter of fig. 4 is referred to as of pseudo-6$^{\text{th}}$ order, while instead it is a 10$^{\text{th}}$ order circuit. The reason for doing so is correlated with the presence of damping. The resistors R_{22} and R_{42} are responsible for damping their associated zeros and poles. All these associated zeros act in the stopband, while all the correlated poles intervene in the high-frequency passband. The level of damping in the BS ISDN splitter is optimized so that, on the one hand, the high-frequency passband of the BS filter is sufficiently suppressed and, on the other hand, the zeros in the stopband still introduce the necessary attenuation. As the damping of 4 out of 10 poles

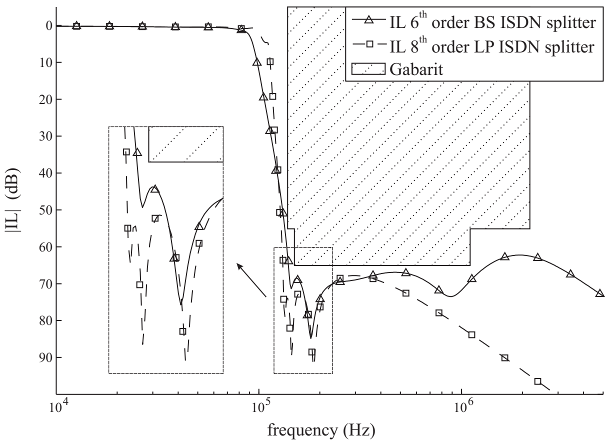

Fig. 5: Comparison of the stopband behaviours for the 8th order LP ISDN splitter and for the pseudo-6th order BS ISDN splitter

in the BS ISDN splitter is fixed to a quite high level, the BS ISDN splitter is referred to as of pseudo-6th order.

V. Comparison of Stopband Behaviour

The two different ISDN splitters of fig. 3 and 4 experience similar behaviour in the passband. The difference in order and topology really becomes visible in the stopband. In order to demonstrate this, the IL behaviour of both splitters in the ISDN 2B1Q mode and in the ISDN-to-LINE direction is presented in fig. 5. From this figure it is clear that the LP ISDN splitter exhibits a more steep IL roll-off than the BS ISDN splitter (cf. difference in order) and that both splitters have their undamped zeros in the lower stopband (138kHz-200kHz). Above 200kHz, the IL-curve associated with the LP ISDN splitter increases at a 40dB/decade rate. In the same frequency range, the IL of the BS ISDN splitter, however, flirts with the gabarit until the end of the stopband due to the 4 damped zeros. For very high-frequencies, also the BS ISDN splitter obtains a 40dB/decade attenuation rate.

VI. Physical Implementation

As stated above, the BS ISDN splitter has one filter stage less than its LP counterpart. This is directly translated in the removal of a large transformer, 2 elliptic capacitors and one high-voltage capacitor. However, the BS topology introduces also 2 new inductors (L_{22} and L_{42}) and resistors (R_{22} and R_{42}). But as these components are not handling any DC current, small surface mount (SMD) versions can be selected.

Figure 6 shows the top and bottom side of a PCB with 4 ISDN splitters and presents the sections that belong to one splitter (dashed white lines). The top side of the panel is filled up with the transformers L_{12}-$L_{12'}$, L_{22}-$L_{22'}$ and L_{32}-$L_{32'}$, and with the high-voltage capacitors C_{22}, C_{42} and C_{62}, and with the SMD inductors L_{22} and L_{42}. The bottom side of the board, on the other hand, is reserved for the elliptic capacitors C_{32}-$C_{32'}$ and C_{52}-$C_{52'}$ together with the damping resistors R_{22} and R_{42}. The LP-to-BS topology change caused an area

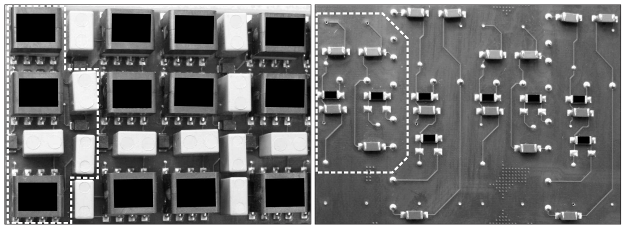

Fig. 6: Top (left) and bottom (right) view of four BS ISDN splitters

profit of more than 25%: the area of four LP ISDN splitters measures 17mm by 42mm (or 7.14cm^2), whereas the area of four BS ISDN splitters is only 17mm by 33mm (or 5.61cm^2).

VII. Conclusion

A new pseudo-6th order elliptic-like ISDN splitter with BS circuit topology is introduced and compared to an actual 8th order elliptic-like ISDN splitter with a traditional LP circuit topology. The ETSI specifications are translated into important BS filter design parameters. The stopband behaviour of both the ISDN splitters is talked over and compared. The physical implementation of the new BS ISDN splitter is presented: the LP-to-BS topology change reduced the amount of filter stages at the cost of a few extra small components, with an overall area-saving of 25% per ISDN splitter.

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